NATIONAL CRITICAL CARE AND TRAUMA RESPONSE CENTRE

Fire Fighter Cooling in Tropical Field Conditions

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Abstract

Aims: To assess the physiological and perceptual responses of fire fighters to a simulated protracted incident in tropical conditions, and to compare the effectiveness of four cooling methods.

Methods: 60 fire fighters participated in a simulated protracted incident that consisted of salvage operations, breathing apparatus confined space operations and simulated HAZMAT containment while wearing fire fighting apparel in field conditions (mean outdoor wet-bulb globe temperature of 29.4°C) for 30 minutes, followed by removal of the fire fighting ensemble for 30 minutes of cooling; repeated 3 times. Fire fighters were assigned to a cooling cohort (1 Shade; 2 Crushed Ice Ingestion; 3 Water Immersion; 4 Misting Fan) matched for body mass index (BMI). During the cooling phase, cohort 1 rested quietly in the shade, cohort 2 ingested 7.5mL.kg^{-1} body mass of crushed ice, cohort 3 were immersed in 25°C water and cohort 4 were seated in front of a misting fan. All 4 groups had ad libitum access to water and/or a carbohydrate/electrolyte beverage. An ingestible telemetry pill permitted measurement of core temperature throughout the exercise, while tympanic temperature, heart rate, blood pressure, subjective thermal sensation and thermal discomfort ratings were recorded periodically throughout the cooling phase.

Results: Overall, pre-exercise core temperature averaged 37.4°C and rose 1.1°C to average 38.5°C following the initial work phase of the exercise, with 5 participants exceeding a core temperature of 39.0°C. Mean core temperature of the water immersion group decreased to average 0.1°C below pre-exercise readings, whereas the shade, crushed ice and misting fan groups averaged 0.3–0.4°C above rest at the cessation of the initial cooling bout. A similar pattern continued throughout the exercise, with the water immersion cohort demonstrating lower mean core temperature following the 2nd work phase (0.5–0.7°C), 2nd cooling phase (0.3–0.6°C) and final work bout (0.3–0.4°C) than the other groups. Thermal sensation was perceived as warm to hot following the initial work bout for all cohorts. 10 minutes of resting in the shade or ice ingestion resulted in thermal sensation improving to slightly warm to warm, whereas the water immersion and misting fan group's thermal sensation improved to slightly cool to cool. After 30 minutes of cooling, the ice ingestion and shade groups felt neutral to slightly warm with the water immersion and misting fan group's maintaining their cool to slightly cool ratings. A similar pattern was repeated across the 2nd and 3rd cooling bouts.

Conclusions: This investigation confirms that physical activity while wearing fire fighting apparel in a tropical environment promotes rapid heat storage. Temperate water immersion is more effective in lowering core temperature than shade, crushed ice ingestion or use of a misting fan during rest periods. For protracted incidents requiring strenous work, a rehabilitation centre with medical support, hydration and cooling inclusive of temperate water immersion is recommended.

Contents

1. Background

1.1. Protective Clothing

A fire fighters protective turnout gear is an occupational requirement, similar to HAZMAT crews or soldiers facing a chemical, biological and/or radiological threat, allowing responders to operate in hazardous environments by preventing injury and ultimately sustaining life. While the protective attire limits heat and chemical transmission from the environment, such insulative properties create a microclimate within the turnout gear that drastically limits the removal of body heat. Ultimately the required evaporative cooling to achieve thermal equilibrium exceeds the capacity of the environment. These conditions are termed uncompensable and alter the physiological challenge presented by physical activity, as heat loss mechanisms are rendered ineffective causing body heat storage until activity is ceased or exhaustion occurs. Responses to uncompensable conditions differ to those of milder environments as highlighted in the following sections

1.2. Responses to Physical Activity in Compensable Conditions

The physiological responses to hot but compensable field and laboratory conditions have been well documented. Physical activity results in heat storage that increases cutaneous blood flow and sweating in an attempt to dissipate such heat. In hot conditions, a narrow gradient exists between skin temperature and that of the environment, causing high cutaneous blood flow and sweat rate (Lee et al., 1995; Patterson et al., 1994) and a decrease in mean arterial pressure (Rowell et al., 1986; Nybo and Nielsen). A compensatory increase in heart rate seeks to meet demand from the active musculature and the cutaneous circuit, resulting in high heart rates during physical activity in hot conditions (Lee et al., 1995; Galloway and Maughan, 1997).

Physical activity in a hot and humid environment elevates peripheral and core tissue temperatures compared with temperate conditions. For example, a moderate bout of cycling in 40ºC results in a core temperature of ~38.9ºC, whereas the same exercise bout in 20ºC produces a core temperature of ~37.9ºC (Parkin et al., 1999). Skin temperatures are also higher during exercise in the heat as demonstrated by the 3–5ºC skin temperature discrepancy between hot and temperate conditions (Adams et al., 1975; Jentjens et al., 2002).

1.3. Responses to Physical Activity in Uncompensable Conditions

Uncompensable conditions exacerbate the responses observed in hot but compensable conditions. In addition to the thermal barrier of the turnout gear, the ~10kg impost not only requires additional work but alters gait and efficiency of movement, increasing internal heat production (Aoyagi et al., 1994). The effectiveness of increases in cutaneous blood flow and sweating in response to the storage of heat are limited due to the restriction of heat transfer through the uniform and its impermeability to water vapour for sweat evaporation.

High sweat rates and cutaneous blood flow causes a hot and humid microclimate to develop within the turnout gear (Chueng and McLellan, 1998), such that even light exercise in 25ºC with protective clothing can result in physical exhaustion in just over 2 hours (Table 1). While the conditions described in Table 1 are relevant year round for tropical regions, fire fighters can experience more severe climates during the summer fire season in the southern states.

Table 1. *Tolerance times (minutes) of 37 Canadian Fire Fighters working in temperate, warm and hot conditions. Table adapted from McLellan and Selkirk, 2006.*

Work Rate	Ambient Temperature		
	25°C	30°C	35°C
Heavy	56.4	47.4	40.7
Moderate	91.9	65.4	54.0
Light	134.0	77.1	67.3

Table 2. *Rectal temperatures at exhaustion during uncompensable heat stress.*

Subjects	Core Temp. (°C)	Reference
Trained	39.4	Tikuisis, et al., 2002
Trained	39.2	Cheung and McLellan, 1998
Trained	39.2	Selkirk and McLellan, 2001
Untrained	38.6	Selkirk and McLellan, 2001
Untrained	38.8	Chueng and McLellan, 1998
Untrained	38.7	Tikuisis, et al., 2002
Untrained	38.8	Selkirk and McLellan, 2001

1.3.1. Physical Exhaustion in Uncompensable Conditions

Physical exhaustion tends to occur at a core temperature of ~40°C for well trained subjects working at a moderate intensity in athletic attire (Gonzalez-Alonso et al., 1999; Nielsen et al., 1993; 1997). The data of Table 2 suggests that protective clothing lowers the core temperature threshold for exhaustion (38.6–39.4°C) compared to more favourable conditions. It is tempting to speculate that the augmentation of blood volume with increased physical fitness confers a superior ability to tolerate heat stress. The expansion of general circulation would permit a higher cutaneous blood volume for a given cardiac output (Rowell, 1986). Yet others (Sawka et al., 1992; Selkirk and McLellan, 2001) found no relation between physical fitness and core temperature at exhaustion in uncompensable heat stress. Furthermore, increasing fitness by 15% and presumably expanding blood volume by 10–15% (Mier et al., 1996) confers no benefit for core temperature, heart rate or tolerance times at uncompensable heat stress exhaustion (Aoyagi et al., 1994). Two weeks of training improves physiological responses to compensable conditions yet no changes are observed during uncompensable heat stress (Cheung and McLellan, 1998). So, rather than the ability to maintain cardiac output during heat stress, the habituation to elevated core temperature that occurs with chronic endurance training may confer high internal temperature tolerance (Selkirk and McLellan, 2001). Regular responding and training in hot conditions is likely to improve the tolerance of NT Fire and Rescue personnel to high core temperatures.

1.3.2. Field Investigations

Subjects from field investigations have greater physiological tolerance to uncompensable heat stress than their laboratory-based counterparts. This conclusion was drawn from an analysis of over 850 experimental trials that identified a median 0.9°C discrepancy for core temperature at exhaustion between settings (Sawka et al., 2001). The higher core temperature in the field could be a result of motivation stemming from actual events as opposed to simulations in a laboratory, or to the chronic acclimatisation status of the field trial subjects. Severely high core temperatures (>41°C) can be observed following competitive running events (Richards et al., 1979; Maron et al., 1977), where motivation may overwhelm the drive for thermoregulation. Although not stringently researched, motivation (monetary rewards) can induce greater thermal stress tolerance to extreme conditions (Johnson and Cabanac, 1983). It's intuitive to expect that the opportunity to save life would have a similar effect on motivation. Field subjects and competing athletes may therefore suppress physiological cues to tolerate higher core temperatures at exhaustion than subjects in laboratory studies. The incongruence between the laboratory and field thermal tolerance (Sawka et al., 2001) encourages assessment of fire fighters in the field rather than the laboratory.

1.3.3. Northern Territory

The aforementioned data establish that wearing protective attire results in potentially dangerous thermoregulatory and cardiovascular stress to the wearer, with a high risk of heat-related illness (House et al., 2003; Ilmarinen et al., 2004; Latzka et al., 1998). Darwin, capital and the most populous locality of the Northern Territory experiences a tropical climate defined into 2 distinct seasons, dry and wet. The dry season typically produces warm to hot ambient temperatures with low to moderate levels of relative humidity (Table 3). The wet season is characterised by hot ambient temperatures and high levels of environmental moisture. While both seasons can present challenges for thermoregulation, the wet season poses the greatest risk of hyperthermia. In their 2006 paper, McLellan and Selkirk (Table 1) demonstrated that the conditions of Table 3 limit fire fighter exposure time to ~41 minutes while undertaking heavy work.

Table 3. *Average environmental Conditions of Darwin, NT (Bureau of Meteorology Darwin Airport Observatory, 12.4°S, 130.9°E)*

Environmental Variable	Dry Season (May – September)	Wet Season (October – April)
Max. Temp (°C)	34.0	34.7
9am Relative Humidity (%)	63.4	76.7
3pm Relative Humidity (%)	41.0	62.3

The wet season, characterised by hot ambient temperatures and high levels of environmental moisture, poses the greatest risk of hyperthermia.

There have been documented cases of people suffering serious injury and death as a result of hyperthermia due to activities undertaken during the wet season in areas proximal to Darwin. Highlighting the potential for thermal injury in such conditions was the death of an Australian Defence Force soldier from heat stress whilst training in the Top End (Cavanagh, 2005) with several other defence personnel hospitalised. Anecdotal reports of medical staff from the Royal Darwin Hospital providing first aid to fire fighters and Northern Territory Emergency Service personnel involved in multi-agency wet season exercises emphasise the risks of responding in a tropical environment.

Currently, in the event of a fire fighting incident in Darwin, responders would be required to work in protective attire with breathing apparatus. Based upon estimated time required to empty a cylinder, approximately 30 minutes of work can be accomplished prior to cylinder change. This 'enforced' break from the incident provides an opportunity to assess the fire fighter and take steps to minimise heat stress, extending the period the fire fighter can continue to respond. Currently there are no definitive guidelines maximising performance of NT Fire and Rescue personnel responding in the heat. Standard Operational Procedure No. 045, Effects of Heat Stress, advises personnel how to minimise heat production, maintain hydration and to recognise the symptoms of heat illness. The sole recommendation for cooling is sponging skin with water and accessing a fan to increase evaporative cooling.

The US National Fire Protection Authority (NFPA) standard 1584 on the rehabilitation process for members during emergency operations and training exercises (2008) is a comprehensive policy covering all aspects of fire fighter welfare. Included within the policy are guidelines to monitor fire fighter vital signs to guide fire fighter management during an incident. Following 20 minutes recovery, a fire fighters heart rate is recommended to be less than 100 beats. minute^{-1}, with systolic and/or diastolic pressure advocated to be lower than 160 and 100mmHg, respectively. Unfortunately, there is no evidence contained within NFPA 1584 to support the efficacy of these recommendations or their validity for other cohorts of fire fighters, including those that work in tropical conditions.

1.4. Cooling Methods

Strategies are required to improve the health and effectiveness of fire fighters operating in uncompensable field conditions. With thermoregulatory mechanisms rendered ineffective by the harsh conditions, exogenous cooling could potentially extend work time, or reduce the duration or frequency of rest breaks required to manage body heat storage. Methods of active cooling studied in uncompensable occupational settings include wearable cooling systems (Cadarette et al., 2002; 2003; McLellan et al., 1999a), the application of ice vests (Barr et al., 2009; Heled et al., 2004; House et al., 2003). immersion of the hands in cool or cold water (Giesbrecht et al., 2007; House et al., 2003; Khomenok et al., 2008), whole body immersion (Peiffer et al., 2010b; Proulx et al., 2003) and spraying participants with water (Heled et al., 2004; Selkirk et al., 2004).

1.4.1. Wearable Systems

Both the Canadian and US military have studied various types of modified personal protective equipment with built-in cooling systems and found that the suits can improve physiological responses and exposure time (Cadarette et al., 2002; 2003; McLellan et al., 1999a). However, McLellan et al. (1999a) acknowledged that this type of suit was not feasible for use by personnel who would be wearing it whilst mobile on land, as it would be too heavy and required a power source (McLellan et al., 1999a). Therefore, despite the desired physiological outcomes, more practical cooling strategies are required.

A parallel field of research has evaluated a series of cooling techniques for athletes. While athletes do not endure the thermal environment of fire fighters, their high intensity physical activity causes rapid body heat storage in hot conditions (Brearley and Finn, 2007; Gore et al., 1993). Therefore, sport scientists have sought to minimise heat storage and maximise performance through the use of practical cooling strategies.

1.4.2. Ice Jackets

The most widely used cooling mode in the field of sports science has been ice compressed against the skin in jackets or vests for pre-cooling and cooling during scheduled breaks. Prior to the 1996 Summer Olympics, Australian Institute of Sport scientists developed ice jackets that slightly blunted the core temperature rise when worn during warm up periods (Smith et al., 1997; Yates et al., 1996). Others have cooled athletes during warm-up periods to achieve cooler core and peripheral temperatures prior to performance. Arngrïmsson et al. (2004) applied the Australian Institute of Sport designed ice jacket during a 38 minute warm up in tropical conditions to lower core temperature by 0.2ºC. Moderate cycling in hot conditions with a cooling jacket resulted in a lower rectal temperature (0.2ºC) following 45 minutes (Hasegawa et al., 2005). Duffield et al. (2003) failed to lower core temperature by applying an ice jacket for 5 minutes before and during scheduled breaks of a simulated hockey protocol. Similarly small gains have been observed for fire fighters during laboratory trials (Bennett et al., 1995), however such benefits are not reproduced when compared to passive rest in temperate conditions (Carter et al., 2007). Medical responders with chemical, biological and radiological personal protective equipment demonstrated an attenuated core temperature response to 30 minutes of work in tropical conditions, a ~0.4ºC benefit compared to resting in the shade (Norton et al., 2010). Combining an ice jacket with an additional cooling method such as forearm water immersion substantially increases its physiological impact, achieving a core temperature decrease of 0.5ºC (Barr et al., 2009).

The primary advantage of utilising garments containing ice for cooling is their practicality, however this advantage is diminished for repeated bouts of use, where the garment requires 're-cooling'. Ice jackets can also hinder movement and work performance due to their bulkiness. Overall, commercially available ice jackets demonstrate a limited potential to curb heat storage during and/or in between bouts of physical activity in hot conditions when used in isolation.

1.4.3. Forearm Immersion

Another practical cooling method is forearm and/or hand immersion in cold water, typically set at 10ºC. Forearm immersion relies on lowering core temperature through convective heat transfer between the blood and forearm tissue (Ducharme and Tikuisis, 1991) and can be effective for repeated work and cooling bouts. Giesbrecht et al. (2007) utilised 3 bouts of working for 20 minutes followed by 20 minutes of 10ºC forearm immersion to lower core temperature by 0.6ºC more than control and 0.3ºC more than 20ºC forearm immersion. 10ºC hand immersion has also provided small physiological benefits when used for only 10 minutes following 50 minutes of work (Khomenok et al., 2008). However, the benefits are not present when compared with passive cooling in an air conditioned room (24ºC) (Carter et al., 2007; Hostler et al., 2010).

We decided against incorporating forearm immersion in the present investigation as the small physiological benefits observed in clinical studies are likely insufficient to counteract the heat storage of fire fighters in tropical field conditions. An additional drawback was the likelihood of limited manual dexterity following hand cooling (Cheung et al., 2003).

1.4.4. Ice Towels

Ice towels have not been stringently researched but are nonetheless recognised as a treatment for hyperthermia (Roberts, 2007), have been used to cool fire fighters (Bull, 2008; Espinosa 2008) and have been trialled as part of pre-cooling procedures for athletes (Duffield et al., 2009; Myler et al., 1989; Ross et al., 2010). Espinosa (2008) applied ice towels during a 20 minute recovery period for fire fighters to lower core temperature by ~0.6ºC, a similar benefit observed for forearm immersion and a small ~0.2ºC improvement over resting in the shade. Ice towels have also been utilised to cool fire fighters in a report by Bull (2008), however the use of tympanic temperature prevents the development of firm conclusions from the data. Medical staff treating hyperthermic runners in the field have used ice towels to lower core temperature (Armstrong et al., 1996; Richards et al., 1979), with cooling rates approximately half the rate observed for cold water immersion. Based on the limited data available, other techniques possess greater potential to achieve a substantial core temperature decrease, leading sport scientists to use ice towels in conjunction with other pre-cooling methods (Duffield et al., 2009; Ross et al., 2010).

1.4.5. Whole Body Immersion

Whole body immersion has been evaluated as a method that can lower pre- and post-activity core temperature, thereby increasing an individual's heat storage potential. The unpredictable nature of fire fighting callouts means that pre-cooling is not practical, however, the physical properties of water make it a suitable method for cooling following heat storage. There appear to be three options for intermittent water immersion, a relatively short immersion (~5 minutes) at cold water temperatures (<15ºC), a moderate immersion of 12–15 minutes in 15–25ºC or a longer immersion protocol of 20–30 minutes in temperate water (25–28ºC).

The limited data available for short duration immersions shows that 5 minutes of exposure to 14ºC water is not effective for thermoneutral subjects (Peiffer et al., 2010a), which is not surprising given that cooling is most effective for individuals suffering heat stress, as high internal temperatures act to limit the effect of local skin cooling on vasoconstriction, allowing greater contact time for blood with the cooled periphery (Casa et al., 2007). The same protocol can lower core temperature by ~0.5ºC for warm/hot subjects (Peiffer et al., 2009a), however there is minimal core temperature difference when immersion in 14ºC is sustained for 5, 10 or 20 minutes (Peiffer et al., 2009b) and minimal differences for 5ºC v 14ºC cooling for 12 minutes (Clements et al., 2002). Extremely cold water (2ºC) is the most rapid method to lower core temperature of hyperthermic individuals with no difference between the cooling rates of 8, 14 and 20ºC due to shivering intensity increasing at lower water temperatures (Proulx et al., 2003). Shivering wasn't observed for 2ºC water immersion as the duration was relatively brief (8.8 minutes) and has been recommended as the treatment of choice for dangerous hyperthermia by a recent large scale review (McDermott et al., 2009). While short duration cold water protocols are effective in rapidly reducing core temperature during hyperthermia, practicality issues arise when operating in tropical field conditions. The availability of the required volumes of ice to initially lower and subsequently maintain water temperature limits the utility of this method. For example, to lower the temperature of a 600L water bath from 25ºC to 2ºC would require ~172kg of ice (Table 4). Therefore, immersion protocols that utilise temperate water are more likely to be achieved in the field. Despite their logistical benefits, less research has examined temperate water as a cooling modality following heat storage. Prior to competition, temperate water immersion is a popular means of pre-cooling as athletes seek to lower their core temperature without inducing shivering. To achieve this, athletes utilise ~30 minutes of 25–28ºC immersion that can lower core temperature by ~0.5ºC (Brearley and Finn, 2006; Marino et al., 1998). If temperate water cooling is effective in lowering core temperature and improving physiological and perceptual strain once an individual has become warm/hot, the possibility of utilising such methods in the field for emergency responders to return to an incident and extend response time warrant consideration.

Table 4. *Volume of ice required to lower water temperature of a 600L bath from 25ºC to desired temperature.*

Desired Water Temperature	20ºC	14ºC	8ºC	2ºC
Ice Requirement (kg)	37.5	82.5	127.5	172.5

Unfortunately, temperate water immersion following heat storage has not been stringently tested. A recent study by Taylor et al. (2008) examined the time to cool core temperature while immersed in 14ºC and 26ºC water following substantial heat storage. While 14ºC water resulted in a faster core temperature decline, Taylor et al., (2008) established that temperate water is an effective modality for lowering core temperature, achieving a cooling rate of 0.1ºC.minute^{-1} for rectal temperature.

1.4.6. Crushed Ice Ingestion

It has been well established that hydration is a strategy that can blunt the rise of core temperature during physical activity. Furthermore, cold fluid consumption results in greater attenuation of core temperature and improved physical performance (Lee et al., 2008; Mundel et al., 2006; Wimer et al., 1997).

Preliminary research suggests that a practical alternative to the previously discussed cooling methods is the ingestion of crushed ice. Commonly referred to as a slurpee or slushie, crushed ice was identified as a possible cooling method for athletes earlier this decade (Brearley and Finn, 2003), as the mechanical cooling properties of ice are far greater than an equivalent volume of cold fluid. For example, consuming 7.5mL.kg^{-1} of crushed ice (-1ºC) lowered core temperature by 0.66ºC whereas an equivalent volume of cold fluids (4ºC) reduced core temperature by 0.25ºC (Siegel et al., 2010). Ihsan et al (2010) demonstrated that crushed ice ingestion also lowers core temperature prior to exercise and that it translates to improved endurance performance. While less research has been conducted utilising crushed ice than alternative modes of cooling, its practicality and preliminary physiological benefits warrant strong consideration for cooling in occupational settings.

1.4.7. Misting Fan

Evaporative cooling is a simple method that can be effective, and is often overlooked for more technically demanding cooling modes. Of the limited research to evaluate the use of misting fans, there is enough evidence to warrant their investigation. Misting fans can improve thermal comfort in tropical conditions (Wong and Chong, 2010), lower core temperature (Espinosa, 2008) and extend work time in uncompensable conditions (Selkirk et al., 2004) but to a lesser extent than other cooling methods. Regardless, the use of misting fans are deemed an appropriate first aid treatment for hyperthermia in the field (Sinclair et al., 2009). The misting fans utilised to date have utilised air velocity of ~2 to ~7 metres.second^{-1}, while spraying less than 10 litres of water.hour^{-1}.

The use of high speed fans and additional water flow substantially greater than that of Sinclair et al. (2009) and Selkirk et al. (2004) may improve the cooling power and the physiological results reported to date and support misting fan application to intermittently cool fire fighters.

1.5 Summary

This investigation aimed to assess the physiological and perceptual responses of fire fighters to a structural fire fighting exercise in tropical field conditions, and to compare the efficacy of four cooling methods during rest periods. On the basis of research from the field of sports science, we predicted that the 3 novel approaches to cooling would more effectively improve physiological and perceptual strain in comparison to the standard approach of resting in the shade. We predicted that the cooling methods would limit the rise in core body temperature sustained by participants during repeated periods of exertion in the heat, reduce the perception of feeling hot and extend the period they were able to respond to an incident.

Our primary objective was to find a method (or methods) of allowing for more effective and safer work by fire fighters during a protracted incident in the tropics. A secondary objective was to find a surrogate physiological marker for core temperature. If a marker such as heart rate, blood pressure or subjective thermal sensation correlated closely with a rising core temperature, we could overcome the need for expensive and invasive core temperature monitoring of fire fighters and provide a convenient method of monitoring the risk of responders developing hyperthermia. Such markers may also influence decisions of whether fire fighters should continue to respond during prolonged incidents.

2. Methodology

Sixty fire fighters (59 men, 1 woman) participated in a simulated fire fighting incident consisting of 3 cycles of 30 minutes work (salvage operations, confined space operations and HAZMAT containment) followed by a 30 minute rest period where subjects were randomised into 4 cohorts (1 Shade; 2 Ice Ingestion; 3 Water Immersion; 4 Misting Fan) matched for body mass index (BMI). The total protocol therefore took 3 hours to complete.

The simulated exercise was conducted on the grounds of Stuart Park Fire Station, Darwin, Northern Territory, Australia over 4 respective days during February, April and May 2009. The subjects to participate on a given test day were randomly assigned to work group 1 or 2. Work group 1 commenced the active phase at 1200, with work group 2 commencing at 1230, coinciding with the commencement of the cooling phase for work group 1. Subjects worked at each of the stations for 10 minutes, one rotation representing 30 minutes of work followed by 30 minutes of rest. This cycle was repeated 3 times according to Figure 1.

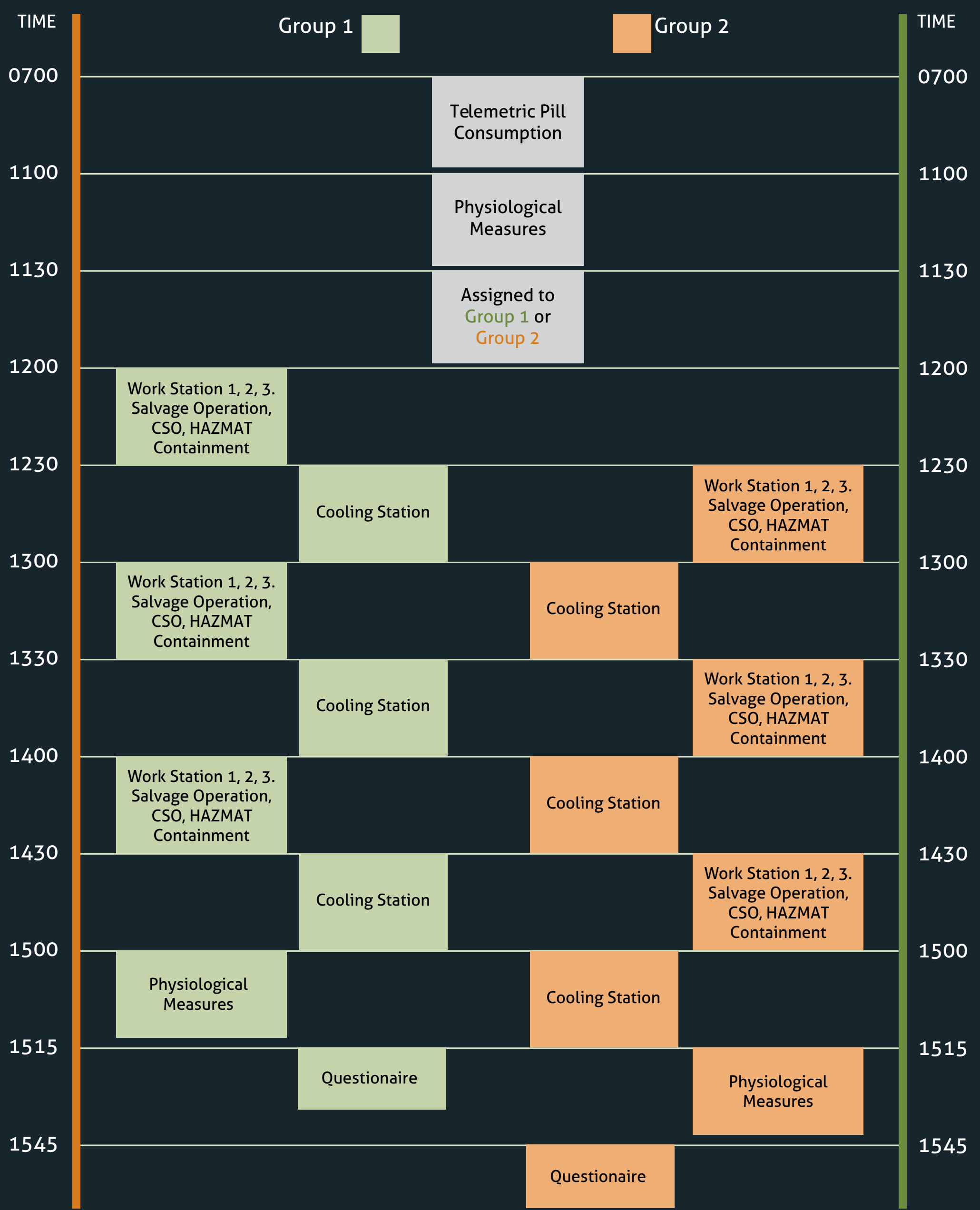


Figure 1. *Experimental schematic of the procedures and their timing.*

2.1. Experimental Design

2.1.1. Work Stations

Immediately prior to the commencement of the exercise, participants applied their bunker jacket and overtrousers comprised of 93% Nomex, 5% Kevlar and 2% Carbon (CTEPPC, Broadmeadows, Victoria, Australia), boots, gloves, helmet and breathing apparatus (PA 94 Plus, Dräeger, Mount Waverly, VIC, Australia) with a combined mass in excess of 10kg. (Figure 2). Fire fighters subsequently commenced the initial work phase at the salvage operation, breathing apparatus confined space operations or simulated HAZMAT containment.

Figure 2. *Fire fighter with turnout gear*

Image courtesy of Joe Stenhouse

2.1.1.1. Salvage Operation

The salvage operation required fire fighters to continuously remove household items from a room within the Stuart Park Training Facility. The items included furniture, carpet and audio-visual equipment (Figures 3 and 4). Where time permitted, the fire fighters would replace the items in the room. At the end of the 10 minute shift, the crews would rotate such that the following crew would start where the previous crew finished. The work was conducted both indoors and outdoors.

Figure 3. *Salvage operation task scene*

Figure 4. *Fire fighter working during the salvage operation task*

Image courtesy of Joe Stenhouse

2.1.1.2. Breathing Apparatus Confined Space Operations

Breathing apparatus confined space operations were performed in the Stuart Park Training Facility, and was therefore conducted indoors (non air-conditioned). Fire fighters manoeuvred through a series of purpose built tunnels simulating movement through a building on fire in full uniform with breathing apparatus under the supervision of an instructor for 10 minutes (Figures 5, 6 and 7).

Figure 5. *Fire fighters working during the breathing apparatus confined space operations*

Figure 6. *Fire fighter working during the breathing apparatus confined space operations*

Figure 7. *Fire fighter working during the breathing apparatus confined space operations*

2.1.1.3. Simulated HAZMAT Containment

Fire fighters worked in pairs to establish a bund wall by filling and emptying sandbags (Figures 8 and 9). This task was performed outdoors and simulated during a HAZMAT situation.

Figure 8. *Fire fighters filling sandbags*

Figure 9. *Fire fighters filling sandbags*

2.1.2. Cooling Stations

At the cessation of a 30 minute work bout, fire fighters walked approximately 100 metres from the work area to the engine room of the fire station and presented to the cooling station they were assigned pre-study.

Cohort 1 fire fighters rested in their fire fighting over trousers and t-shirt within the engine room of the Fire Station (Figure 10).

Cohort 2 rested in the shade and were instructed to consume 7.5mL.kg^{-1} body mass of crushed ice as quickly as possible during the cooling phase. The crushed ice was a 7.2% carbohydrate, electrolyte beverage (Gatorade; Cadbury Schweppes, Melbourne, VIC) made in an automated 'slurpee' machine (Essential Slush Company, Gold Coast, QLD).

Cohort 3 were immersed in baths constructed from non-pressurised 50mm PVC tubing and a liner (Figure 12). The bath dimensions were 1.60m long x 0.84m wide x 0.75m high, creating a maximal water volume of 1.01m^3. Baths were filled to ~60% capacity, creating an approximate water volume of 600L. 1 or 2 fire fighters were immersed in each bath to maximise comfort, however up to 4 athletes are accommodated in the baths during sporting scenarios. Water temperature was maintained at 25ºC by measuring with a digital thermometer (digi-thermo, ACTROL, Melbourne, VIC) and adding cubed ice periodically.

***Figure 10**. Fire fighters in the shade (left) and crushed ice ingestion (right) cohorts during a cooling phase.*

***Figure 11.** Misting fan station.*

Image courtesy of Joe Stenhouse

***Figure 12.** Fire fighters undertaking 25ºC water immersion.*

Image courtesy of Joe Stenhouse

Cohort 4 rested in front of 2 misting fans within a shade tent (Figure 11). Each misting fan was 0.65m in diameter with purpose built irrigation tubing (1.3cm diameter) connected to the front of the fans. Four misting jets sprayed water from the irrigation tubing connected to mains water at a pressure of ~ 43 psi. Fire fighters sat 3 metres from the fan where air velocity was 1.8 metres.second^{-1} with a water flow rate of 60 litres.hour^{-1}.

2.2. Subjects

Northern Territory Fire and Rescue staff and Australian Rescue Fire Fighters who would potentially be required to don fire fighting turnout gear in the event of a fire fighting incident were invited to participate in the study. Participation was voluntary and unpaid, and all participants were fully informed and consented prior to the study, and completed a basic survey of lifestyle factors (Appendix 7.1.), with subject characteristics summarised by Table 5. Subjects were randomised into cooling groups according to BMI. Exclusion criteria included those who were unwell or febrile, unfit to participate in a simulated response exercise, unable to swallow the telemetry pill, and those who had a rapid gastrointestinal tract transit disorder or any form of gastrointestinal obstruction or dysmotility. Ethics approval was granted in January 2009 through the Human Research Ethics Committee of the NT Department of Health & Families and Menzies School of Health Research Northern Territory (Ethics Code 08/80).

2.3. Physiological Measures

2.3.1. Gastrointestinal Temperature

An ingestible telemetric temperature sensor (CorTemp 100, HTI Technologies, Florida, MI, USA) was used as a measure of core body temperature by transmitting a signal proportional to the temperature of the gastrointestinal tract to a handheld receiver. Once located in the gastrointestinal tract, the thermosensitive pill is a valid indice of core temperature when referenced to rectal or oesophageal temperature (O'Brien et al., 1998).

Participants ingested a core temperature pill with fluid prior to breakfast which preceded the commencement of data collection by ~ 4 hours. This timeframe was adopted to allow the pill to empty from the stomach and enter the small intestine while minimising the risk of the pill being emptied from the body prior to the completion of the study (O'Brien et al., 1998). To control for the possibility of local cooling of the telemetry pill via ingestion of fluids and/or crushed ice, subjects were excluded from the study if gastrointestinal temperature was less than 35.5°C, and/or decreased by 2°C in any 5 minute period during the rest phase.

Core temperature was measured evey 10 minutes during work phases and every 5 minutes during rest phases (Figure 13).

Table 5. *Subject Characteristics. Data are Mean (SD)*

Cohort	n	BMI	Mass (kg)	Height (m)	Age (yrs)	Time in NT (yrs)
Shade	15	27.1 (3.7)	84.9 (10.2)	1.77 (0.04)	36.8 (4.6)	24.8 (12.7)
Ice Ingestion	15	27.1 (3.4)	85.6 (10.4)	1.78 (0.05)	34.8 (7.2)	13.9 (11.2)
Water Immersion	15	27.1 (3.1)	86.9 (8.2)	1.79 (0.04)	38.4 (7.3)	24.6 (12.5)
Misting Fan	15	27.7 (3.1)	89.4 (9.8)	1.80 (0.08)	36.0 (5.7)	21.9 (15.1)

2.3.2. Tympanic Temperature

An infrared tympanic thermometer measured tympanic temperature (Thermoscan Pro 3000, Braun, Kronberg, Germany). A sterile probe cover (Thermoscan PC20, Braun, Kronberg, Germany) was attached to the thermometer for each measurement prior to lifting the ear by vertically pulling on the superior aspect of the pinna.

2.3.3. Heart Rate

Heart rate was measured and by a band fitted across the subjects chest (Vantage NV, Polar, Kempele, Finland) and recorded periodically throughout the rest phase.

2.3.4. Blood Pressure

Blood pressure measurements were assessed during the rest period by auscultation of the brachial artery of the right arm. Procedures for blood pressure measurement were according to O'Brien et al. (2001) without prior palpation due to time constraints.

Mean arterial pressure was determined from heart rate, diastolic and systolic blood pressure according to following equation (Moran et al., 1995).

Mean arterial pressure = DBP + (st x PP) (mmHg)

Where st = (0.01exp (4.14 – 40.74))/HR;
DBP = diastolic blood pressure;
HR = heart rate; PP = pulse pressure;
SBP = systolic blood pressure

2.3.5. Anthropometric Measures

Body mass was measured in a semi-nude state (wearing underwear only) on a calibrated scale (UC321, A&D Mercury, Adelaide, SA, Australia). Subjects stood on the scale platform with an even distribution of body mass. Upon establishing a stable reading, body mass was recorded to the nearest 0.05kg.

Stature was measured as the greatest vertical distance between the floor and vertex of the head with a calibrated stadiometer (Len Blaydon, Lungarno, NSW, Australia). To achieve an accurate measurement, subjects stood with heels touching the stadiometer and were instructed to take a deep breath while looking straight ahead with their head in the Frankfort plane. The stadiometer headboard was lowered to contact the vertex of the head to permit measurement of height to the nearest millimetre (mm). The stadiometer was routinely calibrated against a steel rule.

Figure 13. *Subject having core temperature assessed.*

Image courtesy of Joe Stenhouse

2.3.6. Hydration Status

Urine specific gravity was assessed with a refractometer (Atago URC-NE, Tokyo, Japan). Refractometers permit the measurement of dissolved solids in liquids by passing light through a liquid sample and showing the refracted angle on a specific gravity scale. A greater density reflects lower hydration status.

A one-point calibration with distilled water (Elgacan, Elga Ltd, Bucks, England) was performed prior to testing of urine specimens. Distilled water (dH_2O) was allowed to equilibrate to room temperature for one hour prior to calibration. Approximately 60μl of dH_2O was placed on the specimen plate for analysis. The lid was closed gently ensuring a thorough and even spread of the dH_2O over the specimen plate. The refractometer was raised to the researcher's right eye in a well-lit laboratory and the refractive index was aligned with 1.000 by turning a small screw atop the refractometer.

The specific gravity of urine specimens was determined by observation of the scale with a urine sample on the specimen plate. Upon determination the specific gravity was manually recorded. Following specimen analysis, care was taken to thoroughly clean the refractometer specimen plate by washing with distilled water and drying with sterile gauze (Handy, BDF, Sydney, NSW, Australia). Urine specific gravity values were subsequently compared to the index of hydration status from Casa et al., (2000).

All 4 groups had ad libitum access to fluids, which included an electrolyte, carbohydrate replacement drink (Gatorade, Cadbury Schweppes, Melbourne, Australia) made to half strength (3.6% carbohydrate) and water. Both were served at a temperature of 16–20°C. The crushed ice was a 7.2% carbohydrate, electrolyte beverage (Gatorade; Cadbury Schweppes, Melbourne, VIC) made in an automated 'slurpee' machine (Essential Slush Company, Gold Coast, QLD).

2.3.7. Dehydration, Fluid Consumption and Sweat Rate

Dehydration was estimated from body mass change from pre- to post-exercise. Subjects were weighed semi-nude prior to changing into fire fighting attire. Post-exercise, fire fighters removed their attire and towelled non-evaporated perspiration from the skin and hair prior to body mass measurement. The resultant dehydration estimation was expressed as a percentage of pre-study body mass by the following equation.

Dehydration (%) =
(Body Mass Loss / Pre-Study Body Mass) x 100

Where body mass loss and pre-study body mass are reported in kg.

Fluid consumption was monitored by weighing the subjects individual bottle (Figure 14) prior to and following each rest period, with the difference representing fluid consumption during the rest period.

Subjects were weighed prior to and following toilet breaks (if required) to determine urine/faecal output.

Sweat Rate ($L.h^{-1}$) =
(Dehydration + Fluid Consumption – Urine and Faecal Output) / Time

Where dehydration, fluid consumption and urine and faecal output are expressed in kg. It was assumed that one kg was equivalent to one litre of fluid. Time is reported in hours.

Figure 14. *Individual drink bottles.*

Image courtesy of Joe Stenhouse

2.3.8. Perceptual Measures

Subjective thermal sensation was recorded using the modified numeric and descriptive scales of Gagge et al., developed in 1967. Participants were asked 'How does your body temperature feel?', with a numerical rating of 7 corresponding with the descriptor 'neutral' (Appendix 7.2.). Ratings of 1–6 equate to unbearably cold to slightly cool, while 8–13 correspond with slightly warm to unbearably hot.

2.3.9. Data Collection Logistics

Safety was a primary consideration of this study, with safety officers present to assist with applying and removing turnout gear and breathing apparatus (Figure 15), and supervising the exercise at all stages. There was at least 1 fire fighter per 3–4 participants during the active phase of the exercise, plus another 'floating' fire fighter who supervised all the active participants. There were also at least 2–3 fire fighters per cooling station, and a 'floating' fire fighter supervising the cooling area. There were several doctors present at each study, including Emergency Department (ED) residents, ED registrars and an ED consultant, and a Thomas pack was available in case any treatment was required. All of the fire fighters and doctors were working voluntarily.

In addition, there were multiple volunteers involved in recording observations on participants at the cooling stations. There was one volunteer per 2–3 participants at each cooling station measuring heart rates, blood pressures, tympanic temperatures, thermal sensation scores and thermal discomfort scores. These volunteers included doctors, nurses, medical students and physiotherapists.

At all times there were 2 volunteers measuring and recording core temperature readings on the participants in the active phase of the exercise, and 2 volunteers conducting core temperature measurements on those in the cooling stations. These volunteers included exercise physiologists from the NT Institute of Sport, and nurses. There was also an exercise physiologist in charge of preparing, administering and measuring the carbohydrate, electrolyte beverage and/or water for all participants, in addition to preparing and administering the crushed ice drinks for cohort 4 at their cooling station. Additionally, the Fire Station Manager and an Emergency Physician oversaw the entire operation. This resulted in a total of at least 30 volunteers helping on each study day.

At the completion of the study the participants' final weight was measured and recorded, a post study urine sample was collected, and calculated the quantity of fluid consumed. Participants filled in a post-exercise survey on how they felt at the completion of the study, as well as how practical they found the experimental cooling methods (Appendix 7.3.).

2.3.10. Environmental Conditions

On each of the 4 study days environmental data (ambient temperature, apparent temperature, wet bulb temperature and globe temperature) was acquired from the Bureau of Meteorology Darwin Airport Weather Station (station number 014015) as calculated according to the WBGT equation (www.bom.gov.au). The weather station was 4.8km from the Stuart Park Fire Station. Environmental measurements were documented every 30 minutes during the period from 1200–1530 when the study was conducted.

$$WBGT = (0.7 \times Tnwb) + (0.2 \times Tg) + (0.1 \times Ta)$$

Where Tnwb = natural wet bulb temperature (represents integrated effects of humidity, radiation + wind); Tg = black globe temperature (represents integrated effects of radiation + wind); Ta = ambient temperature

Figure 15. *Fire fighters preparing to re-enter the work scene.*

Image courtesy of Joe Stenhouse

3. Results and Discussion

3.1. Study Completion

Technical limitations and individual differences in gastric motility limited the core temperature cohort to 45 subjects (10 shade; 11 ice ingestion; 13 water bath; 11 misting fan). The subject characteristics of the 45 subjects are detailed by Table 6. The 15 excluded subjects were deemed to have the pill located in the stomach (13) by demonstrating core temperatures <35.5°C and/or a 2°C decrease within a 5 minute period or had voluntarily withdrawn from the investigation due to feeling unwell (2). Both subjects were examined by medical staff, had normal observations and were medically cleared.

The dependant variable core temperature and its potential surrogate markers (heart rate, mean arterial pressure, thermal sensation) were therefore limited to the 45 subjects with valid core temperature data. The 13 subjects with invalid core temperature data were included in the analysis of fluid balance variables, resulting in a cohort of 58 subjects.

Table 6. *Subject Characteristics. Data are Mean (SD)*

Cohort	n	BMI	Mass (kg)	Height (m)	Age (yrs)	Time in NT (yrs)
Shade	10	27.5 (3.5)	85.8 (10.3)	1.77 (0.03)	37.6 (5.0)	24.2 (13.4)
Ice Ingestion	11	27.3 (3.4)	85.3 (8.3)	1.77 (0.05)	35.0 (6.3)	14.5 (12.6)
Water Immersion	13	27.6 (2.9)	88.5 (7.8)	1.79 (0.04)	38.9 (7.2)	25.5 (12.6)
Misting Fan	11	28.6 (2.4)	93.0 (9.1)	1.80 (0.06)	36.7 (5.4)	22.1 (13.9)

3.2. Environmental Conditions

KEY POINT Relatively mild environmental conditions were encountered during this investigation. The conditions responses during the rest phase, but likely to have had less influence on the responses during the work phase.

Environmental conditions varied across the 4 data collection days with days 3 and 4 occurring during the early stages of the dry season.

Overall the environmental conditions experienced during the study are considered to be milder than typical wet-season conditions, due to the moderate conditions experienced during days 1, 3 and 4 (Table 7). Mean maximal daily temperature for April and May during 2008 – 2010 were 33.1 and 32.5°C, respectively, well above the mean ambient temperatures for days 3 and 4 of this investigation. Therefore, the data of this investigation are considered conservative responses for a tropical environment. This also means results from this study could be applicable to all Australian states at the height of the southern fire season, or during combat of fires during the summer months.

Table 7. *Environmental Conditions during Data Collection for WBGT calculation see 2.3.10.*

Environmental Variable (°C)	Day 1	Day 2	Day 3	Day 4	Overall
Mean Ambient Temperature	27.0	32.2	30.8	28.6	29.5 (2.3)
Mean Apparent Temperature	28.8	31.9	28.6	23.9	28.6 (3.0)
Mean WBGT	31.5	31.8	28.5	24.1	29.4 (3.2)
Ambient Temperature Range	25.5 – 27.9	31.5 – 32.6	30.0 – 31.6	27.5 – 29.4	25.5 – 32.6
Apparent Temperature Range	26.4 – 30.5	31.3 – 32.5	26.2 – 30.3	22.6 – 24.5	22.6 – 32.5
WBGT Range	30.1 – 32.1	31.3 – 32.6	25.1 – 29.9	23.4 – 24.5	23.4 – 32.6

3.3. Gastrointestinal Temperature

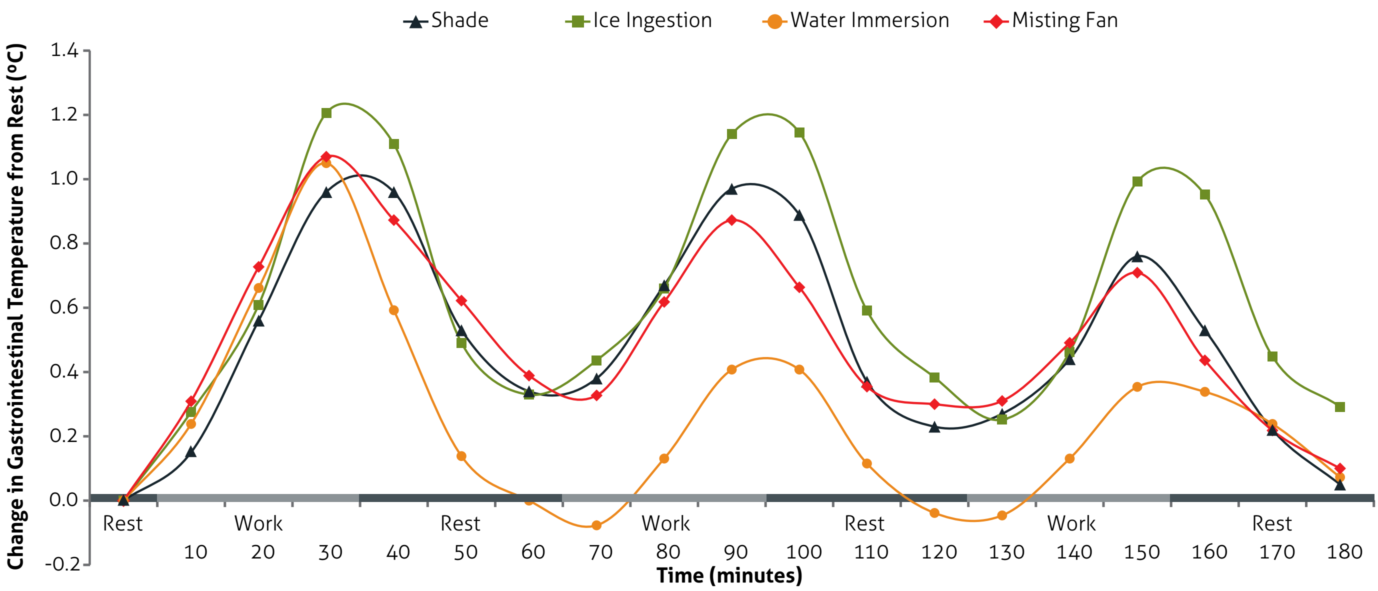
KEY POINT 25°C water immersion was more effective in lowering core temperature than resting in the shade, resting in front of a misting fan or ingestion of crushed ice.

Pre-exercise core temperature averaged 37.4°C and rose 1.1°C to average 38.5°C following the initial work phase, with 5 participants exceeding a core temperature of 39.0°C.

Mean core temperature of the water immersion group decreased to average pre-exercise readings, whereas the shade, crushed ice and misting fan groups averaged 0.3–0.4°C above rest at cessation of the initial cooling bout. A similar pattern continued throughout the exercise, with the water immersion cohort demonstrating lower mean core temperature following the 2nd work phase (0.5–0.7°C), 2nd cooling phase (0.3–0.6°C) and final work bout (0.3–0.4°C) than the other groups (Figure 16). For a larger version of Figure 16, see Appendix 7.4.

We anticipated a cumulative increase in core temperature from exercise phase 1 through 3. However, this core temperature 'drift' failed to eventuate, likely due to pacing by the fire fighters in response to their physiological cues. Unlike laboratory investigations that standardise workload (generally done on a treadmill), this was a field study, where work rates could not be precisely controlled as per the lab. To overcome this, each work station had a minimum of one fire fighter supervising and encouraging the participants to complete their task and a research team member timed each workstation bout to 10 minutes. Despite these control mechanisms, it's probable that the shade, ice ingestion and misting fan cohorts paced their efforts. Anecdotal reports from the research team suggested a notable decrease in work output across the exercise phases, which is not surprising given that standard Operational procedure No. 045 of the NT Fire and Rescue Service (1995) recommends that fire fighters behave sensibly to minimise heat stress, including sensible work pacing. Participants in the water immersion group describe feeling energetic and less fatigued compared to colleagues in other cooling groups. Pacing is common in sporting scenarios where work output in the 2nd half of a sporting fixture is lower than in the 1st (Coutts et al., 2010; Özgünen et al., 2010).

Figure 16. *Response of gastrointestinal temperature to the respective phases of exercise and cooling.*



The phenomenon of pacing should not be under-estimated. Work output improvements, were not specifically tested in this study, but anecdotally reported by numerous candidates in the water immersion group. A fire-fighting workforce better able to sustain high work outputs without being limited by "pacing" would ensure a more effective rescue and less time over-all exposed to heat and other dangers in the fire zone. This benefit can be considered as a secondary "output" gain as well as a safer work environment.

The work phases were simulated tasks. It's foreseeable that the participants would tolerate greater thermal stress prior to regulating work rate if the situation was a genuine emergency response. An alternative explanation is that the onset of fatigue limited the ability of the fire fighters to continue their task at similar rate to the initial work bout.
This notion appears remote based upon the observed physiological responses. While uncompensable conditions appear to interact with physical activity to lower core temperature at fatigue, the mean core temperatures of this study do not suggest the fire fighters were approaching exhaustion.

Based upon the core temperature response to the 3 work and rest phases, the most effective cooling mode was the 25ºC water immersion. Specific discussion of each cooling are explained in the following sections.

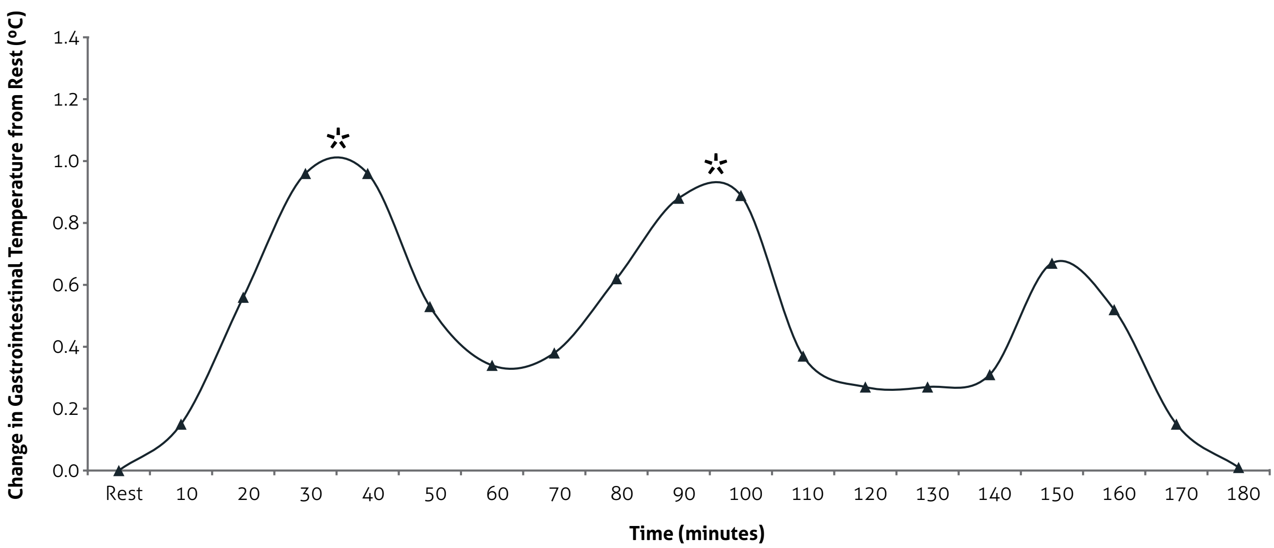
3.3.1. Shade

KEY POINT 30 minutes of resting in the shade in warm/hot tropical conditions decreases core temperature by ~0.6ºC.

The shade cohort acted as the control group for this investigation. Subjects removed their turnout coat to rest in t-shirt and over trousers as per current practice to lower core temperature by a consistent 0.62, 0.61 and 0.66ºC across the 3 rest phases (Figure 17). As represented by * in Figure 17, 10 minutes of resting in the shade failed to lower core temperature as metabolic heat production remains elevated following the preceding work phase and heat from the deep tissues requires

The 0.6ºC decrease achieved by resting in the shade was insufficient to offset the heat storage during the initial work phase. As discussed in Section 3.3., we hypothesise that pacing prevented a cumulative increase in peak core temperature across the work phases. Extrapolating the heat storage observed during the initial work phase predicts that fire fighters would achieve average core temperatures of 38.5 to 39.0ºC at the cessation of the 2^{nd} work phase, warranting more aggressive cooling strategies to extend fire fighter response time beyond 2 rotations and limit pacing as a heat storage management strategy.

Figure 17. *Shade cohort's gastrointestinal temperature response to the respective phases of exercise and cooling. * note the steady core temperature during the initial 10 minutes of cooling during the 1^{st} and 2^{nd} rest phases.*



3.3.2. Ice Ingestion

KEY POINT Fire fighters struggled to consume required volume (7.5mL.kg^{-1} body mass) of crushed ice. The cooling effect of the crushed ice was not sustained during work periods.

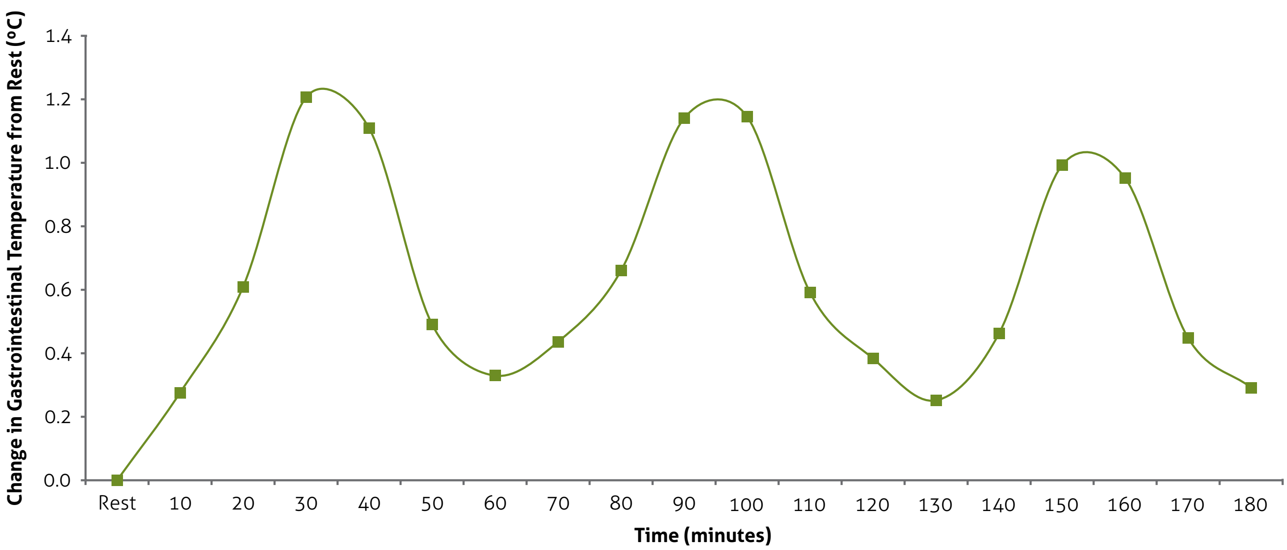
Based upon the promising results observed when athletes consumed crushed ice prior to competition (Seigel et al., 2010, see Section 1.4.5.), we anticipated that fire fighters would rapidly lower their core temperature following crushed ice ingestion. An unforeseen issue was the inability of the fire fighters to consume the required 7.5mL per kg body mass in a rapid manner. Based upon the average body mass of the ice ingestion cohort, 0.64L was to be ingested. Anecdotal feedback from the fire fighters was that they struggled to consume the allotted volume, causing some of the ice to melt prior to consumption. The most common reasons for failing to ingest the ice prior to melting was an "ice-cream headache". Overall fluid consumption for the ice ingestion group was lowest of all cohorts for each of the three cooling periods. A recent presentation of data from the only other investigation to examine crushed ice ingestion in an occupational setting showed that miners consumed 34% less crushed ice when compared to cold fluids (Máte et al., 2010). In that study, despite the lower ice consumption, core temperature was not different between the groups due to the cooling power of the ice. Conversely, we don't see the expected improvement in core temperature for the ice ingestion cohort when referenced to the other groups.

Table 8. *The decrease in core temperature during the rest phase.*

Cohort	Rest Period		
	1	2	3
Shade	0.62	0.61	0.66
Ice Ingestion	0.98	0.76	0.70
Water Immersion	1.05	0.45	0.32
Misting Fan	0.68	0.57	0.61

The crushed ice assisted in lowering core temperature by an average 0.98ºC (Figure 18), similar to that of the water bath (1.05ºC) and better than the shade group (0.62ºC) as represented by Table 8. Unfortunately, the cooling wasn't sustained as the crushed ice group stored more heat than the other cohorts in the subsequent work phases by 0.2–0.4ºC. The most interesting finding for the ice ingestion group was that despite doing similar work, the ice ingestion group averaged a higher core temperature than the other groups at the end of the initial work phase by 0.2–0.3ºC. A similar pattern continued throughout the work phases, such that despite a similar core temperature upon commencing the 2nd and 3rd work phases between the ice ingestion, shade and misting fan cohorts, the ice ingestion group had higher core temperatures. Until additional research is available, we are unable to account for this response.

Figure 18. *Ice Ingestion cohort's gastrointestinal temperature response to the respective phases of exercise and cooling.*



The crushed ice was effective in lowering core temperature during the initial rest phase as detailed in Table 9, achieving an 81%reduction in peak core temperature, however the cooling effect was not sustained. Based upon the sport science studies, ice ingestion is a powerful cooling technique that requires tailoring to meet the needs of fire fighters. Whereas athletes are accustomed to consuming large volumes, it's likely that fire fighters will require time to develop the capacity to ingest an adequate volume of crushed ice to make a meaningful improvement to their core temperature that can be sustained throughout work in uncompensable conditions. Use of cool fluids (Burdon et al., 2010) or crushed ice should not be discounted as a useful adjunct to be administered along with other cooling methods.

Table 9. *Percentage decrease in core temperature during cooling phase.*

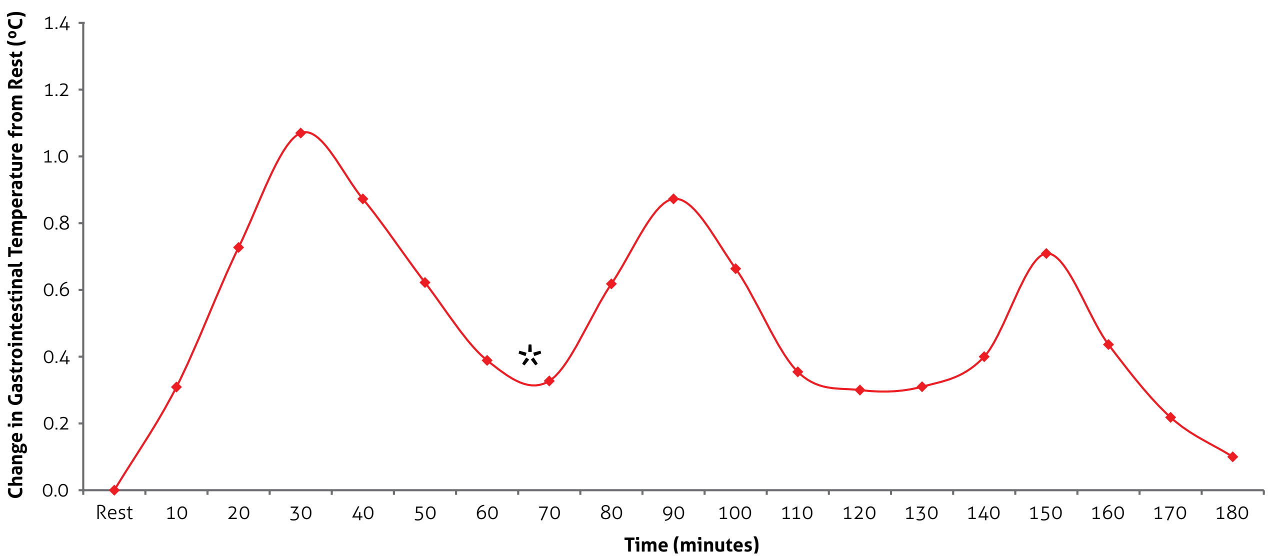
Cohort	Core Temperature Percentage Decrease during the Initial Cooling Phase
Shade	65
Ice Ingestion	81
Water Immersion	100
Misting Fan	64

3.3.3. Misting Fan

KEY POINT The misting fan lacked the overall cooling power of water immersion.

Figure 19 demonstrates that the misting fan lowered core temperature in a similar manner to resting in the shade, and is therefore considered not effective in the manner used during this study (high volume misting and high velocity fans). For misting fans to have a meaningful impact, the evaporative potential for sweat should be improved. It appears in this investigation that the combination of air and water flow could have been too high, therefore limiting sweat rate due to cool skin temperatures, as several subjects reported feeling uncomfortably cold during their exposure and required a break from the cooling. Furthermore, the decrease in core temperature during the initial 10 minutes of the 2nd work bout suggests that the cooled skin and subcutaneous tissues acted as heat sinks upon rewarming (denoted by ⁎ in Figure 19). On the commencement of the work bouts following cooling, increased blood flow through the cooled limbs would result in cooling of the blood and ultimately the core via counter current (blood to blood), convective (blood to tissue) and conductive mechanisms (tissue to tissue) (Mittleman and Mekjavic, 1988), a phenomenon termed the 'afterdrop'.

Figure 19. *Misting Fan cohort's gastrointestinal temperature response to the respective phases of exercise and cooling. ⁎ note the small core temperature afterdrop following the 1st rest phase.*



Afterdrops are usually observed following water immersion bouts rather than for exposure to misting fans, reinforcing the cooling of the limbs. Because the afterdrop was observed in our misting fan group, we postulate vasoconstriction, lack of sweating and shunting of blood away from chilled skin may have actively limited the heat loss of these individuals. Given that the fire fighters attire was already saturated with sweat from the work bout, sufficient cooling may have occurred by use of a fan without the misting. Evaporative cooling by a high speed fan remains an option. Additional trials can address the need for misting and the required volume of water and air velocity.

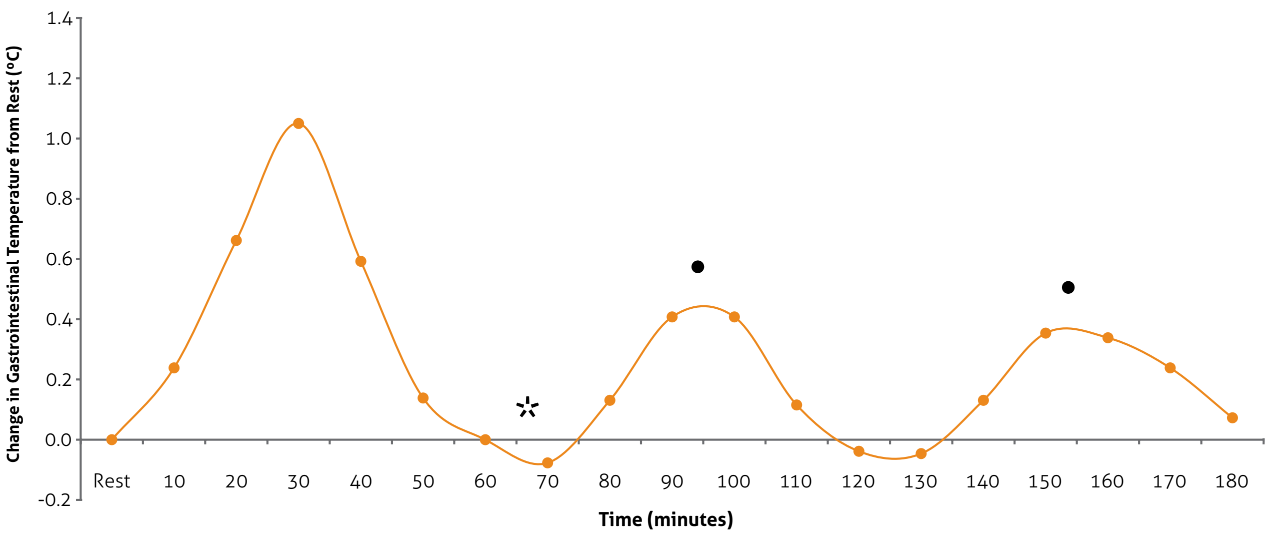
3.3.4. Water Immersion

KEY POINT 25°C water immersion was the most effective cooling method.

The primary limitation of water immersion cooling in the field has been logistical, providing the rationale for use of alternative cooling methods that require minimal setup and monitoring. However the cooling power of water immersion has prompted sport scientists to re-evaluate the practicality of field water immersion and subsequently utilise this method prior to and during half-time periods of international sporting competitions, including those conducted in Beijing, China (personal observations). Hence, the logistical issues can be managed to make water immersion a suitable method for high pressure scenarios such as Olympic competition, where space and resources are limited.

This study utilised 25°C water and a purpose built portable pool to improve its utility in the field. The authors have previously used small inflatable swimming pools, and recommend their use where purpose built equipment is not available. Mains water in the greater Darwin region can vary between 24–30°C depending upon the season, meaning that minimal ice is required to achieve desired temperature.

Figure 20. *Water immersion cohort's gastrointestinal temperature response to the respective phases of exercise and cooling. ⁕ note the core temperature afterdrop following the 1st rest phase. ● denotes depressed peak core temperature during the 2nd and 3rd work phases.*



The core temperature results support the use of water immersion for fire fighters during rest periods in tropical conditions. Figure 20 demonstrates that 30 minutes of immersion returned core temperature to resting levels, with core temperature continuing to fall during the initial 10 minutes of work periods 2 and 3, respectively. As for the misting fan cohort, an afterdrop was observed that limited the increase in core temperature during the 2^{nd} and 3^{rd} work phases to ~0.4°C (represented by ⁕ in Figure 20). Such heat storage meant that the average core temperature of the water immersion group did not exceed 37.8°C during the 2^{nd} and 3^{rd} work phases (represented by ● in Figure 20). Such a response exceeded the expectations of the research team and provides scope to shorten the water immersion protocol. The objective of any rest period for fire fighters is to improve their physiological and perceptual well being and extend their response to and work output during an incident. Shorter rest periods would permit a greater work time, with the following section discussing optimal work to rest periods based upon the water immersion results.

3.4. Work:Rest Ratio

KEY POINT 30 minute work rotations followed by 15 minutes of 25°C water immersion will substantially extend the work time required to increase core temperature by 1.5°C.

Heat storage of 1.5°C while in uncompensable conditions is considered to have a significant physiological impact on a fire fighter. Therefore, a core temperature increase of 1.5°C was used as criteria to assess variations to the 30 minutes of work and 30 minutes of rest used by this investigation. We specifically examined the cooling rates following the initial work bout to model the impact of shortening the rest period to 10, 15 and 20 minutes (Table 10).

The analysis predicts repeated bouts of 30 minutes work to 10 minutes of cooling (30:10) would be insufficient for fire fighters to finish 2 work bouts if shade, ice ingestion or a misting fan were used as cooling modes (14.1 to 28.8 minutes into second work bout). Conversely, fire fighters would extend their response time to ~21 minutes into a third work bout if 10 minutes of 25°C water immersion was utilised during rest periods.

A similar trend was observed for 30 minutes of work followed by 15 minutes of cooling (30:15). Water immersion is predicted to permit fire fighters to almost complete 4 work bouts (161.4 minutes) whereas ice ingestion, shade and misting fan groups would complete 2 complete work bouts.

KEY POINT In scenarios where resting in the shade is the recovery mode, a maximum of two 30 minute rotations is recommended.

A 30:20 work to rest ratio further extends the number of work bouts completed where 25°C water immersion is undertaken to approximately 11. It should be noted that these predictions are conservative, with any afterdrop not properly accounted for. Hence, time to reach the threshold temperature is likely to be slightly longer than reported here.

The modelling suggests that 15–20 minutes of 25°C water immersion as a replacement for resting in the shade will substantially extend response time in the tropical conditions studied. Given that removal and replacement of protective equipment prior to and following the water bath is expected to take ~5 minutes, 20 minutes of rest, incorporating 15 minutes of 25°C water immersion is recommended as the appropriate combination of cooling and practicality for NT fire fighter management.

Table 10. *Time (minutes) to increase gastrointestinal temperature 1.5°C above pre-test value based upon the initial 30 minutes of work and 10, 15 or 20 minutes of cooling.*

Cohort	Minutes of Cooling		
	10	15	20
Shade	62.5	96.4	141.5
Ice Ingestion	54.1	84.8	125.0
Water Immersion	101.3	161.4	541.7
Misting Fan	68.8	107.6	120.5

3.5. Surrogate Markers of Core Temperature

Surrogate markers of core temperature would be useful to those observing and treating fire fighters in rehab or rest areas during a major incident. Physiological or perceptual values or scores that correlated exactly with core temperature were sought, to allow non-invasive testing to accurately estimate core temperature. Results and discussion on each marker are outlined in the following section.

3.5.1. Tympanic Temperature

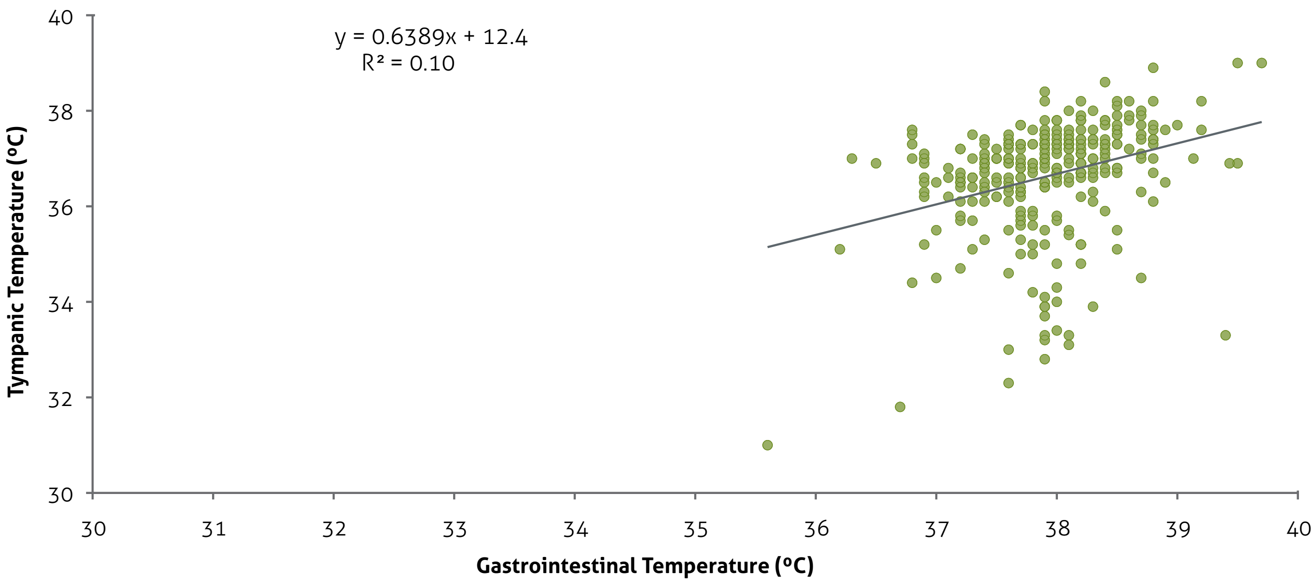
KEY POINT Tympanic temperature should not be used to measure or predict core temperature of fire fighters responding to an incident.

The cost effectiveness, ease of measurement and relatively non-invasive nature of tympanic temperature measurement promote this site as an alternative to measurement of fire fighters gastrointestinal temperature. While some laboratory settings provide an environment where adequate accuracy for tympanic temperature can be achieved (Amoateng-Adjepong et al., 1999; Christensen and Boysen, 2002), tympanic temperature averaged 1.3°C below gastrointestinal temperature in the current study.

On 17 occasions tympanic temperature was measured below 34°C, highlighting its potential to provide a misleading approximation of core temperature. A major limitation of tympanic temperature is that any factor that alters temperature of the face can locally influence temperature of the ear canal (Desruelle and Candas, 2000). The use of tympanic probes (Sato et al., 1996) and insulation of the ear (Muir et al., 2001) could limit these issues, however the requirement for exact positioning, irritability of the ear canal and a decreased ability to detect aural cues mean that tympanic probes are not practical for management of fire fighters during an incident.

As demonstrated by Figure 21, the correlation between tympanic and gastrointestinal temperature is weak (r = 0.31), with many outliers, meaning that tympanic temperature cannot be used as a simple predictor of core temperature. Gastrointestinal temperature averaged 1.3°C higher than tympanic temperature with only 12 of the 293 readings reporting tympanic temperature higher than that measured from the gastrointestinal tract. Extreme examples include gastrointestinal temperatures of 39.4°C, 37.9°C and 37.6°C with corresponding tympanic temperatures of 33.3°C, 33.2°C and 32.3°C, respectively. The USA National Fire Protection Association (NFPA) recognise the limitations of tympanic temperature for management of fire fighters, with standard 1584 stating tympanic temperature can be up to 1.1°C lower than core temperature, and cannot be relied upon to exclude the possibility of heat related issues.

Figure 21. *Scatterplot of gastrointestinal temperature and tympanic temperature during the cooling phases (n=293 observations)*



3.5.2. Heart Rate

KEY POINT Rather than predicting core temperature for a given heart rate, fire fighters are recommended to achieve a heart rate of less than 120 beats.min^{-1} prior to incident re-entry.

Figure 22 demonstrates a moderate correlation between core temperature and heart rate (r=0.48). The correlation did not improve by limiting the data to the mid and end point of cooling. We sought a simple estimation of core temperature that could be utilised in the field. While models exist, they require multiple inputs and are considered cumbersome due to their complexity (Yokata et al., 2008). With large numbers of outliers, heart rate on its own is considered insufficient to be relied upon as a simple surrogate marker for core temperature. As opposed to a discrete heart rate representing a corresponding core temperature, a threshold heart rate is more appropriate to determine whether fire fighters ought to re-enter an incident.

NFPA 1584 states that a fire fighter who has not achieved a heart rate less than 100 beats per minute following 20 minutes of rest should not be released from rehabilitation, and undergo further monitoring. Such a standard would have ruled out the re-entry of 17 (37%) participants of the current study based on the heart rate measured at 25 minutes of the initial cooling phase (Table 11). The average gastrointestinal temperature of those 'excluded' subjects was 37.8°C, a mere 0.4°C above resting values, and none could have been considered fatigued or feeling unwell.

Table 11. *Number of fire fighters with a heart rate of greater than 100 beats per minute during the initial cooling phase*

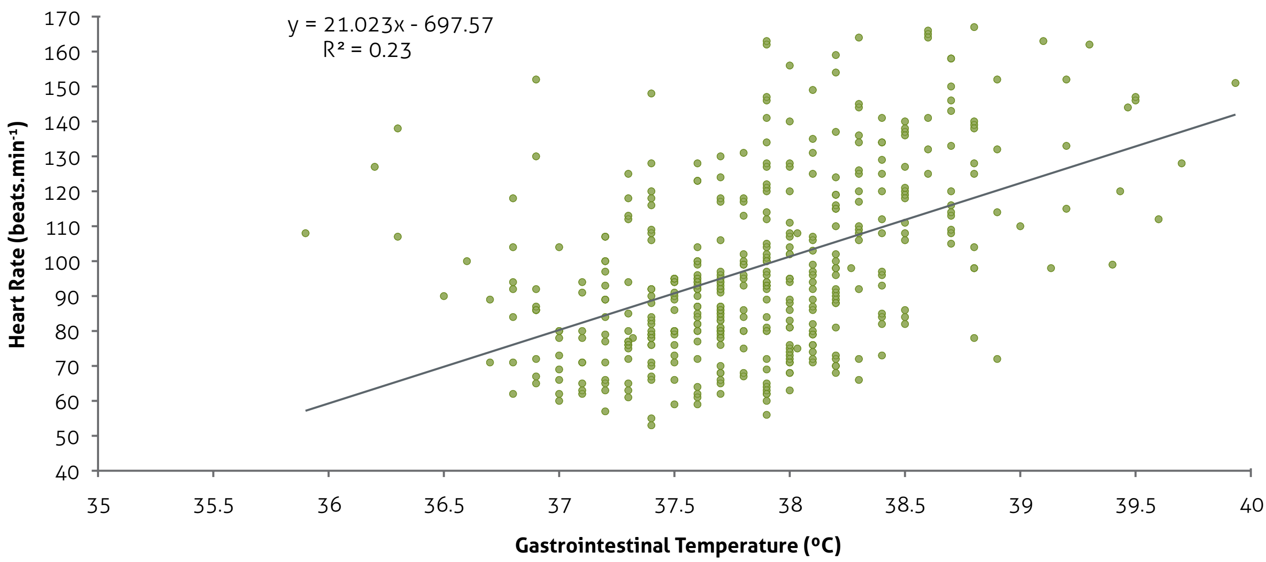
Cohort	Frequency
Shade	6
Ice Ingestion	6
Water Immersion	3
Misting Fan	2
Total	17

The NFPA 1584 standard may be too conservative to manage the response of fire fighters in the Northern Territory. Altering the exclusion threshold modifies the number of fire fighters re-entering the incident according to Table 12.

Table 12. *Number of fire fighters prevented from re-entering the incident following the initial cooling phase with a range of heart rate thresholds*

Heart Rate Threshold	Restricted Personnel
100	17
110	5
120	1
130	1
140	0

Figure 22. *Scatterplot of gastrointestinal temperature and heart rate during the cooling phases (n=433 observations)*

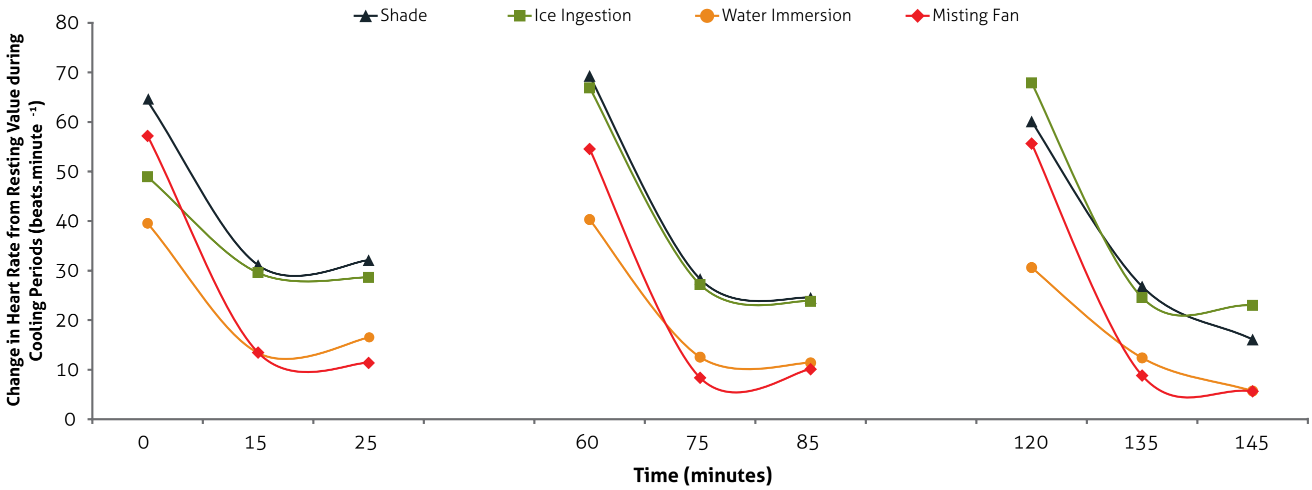


Five subjects exceeded a heart rate of 110 approaching the end of the cooling periods, averaging a corresponding gastrointestinal temperature of 38.0°C. Adjusting the heart rate threshold to 120 beats per minute reveals that one subject exceeded this limit, also with a core temperature of 38.0°C. This same candidate also exceeded the 130 beats per minute threshold at the end of the initial work phase and therefore appears twice in Table 12. None of the aforementioned subjects demonstrated symptoms of EHI and were deemed fit to continue. Acknowledging that a single criterion is unlikely to substitute for core temperature and based upon the observations of this investigation, we recommend that Northern Territory Fire Fighters achieve a heart rate of less than 120 beats per minute prior to incident re-entry.

3.5.3. Differences between the Cooling Modes

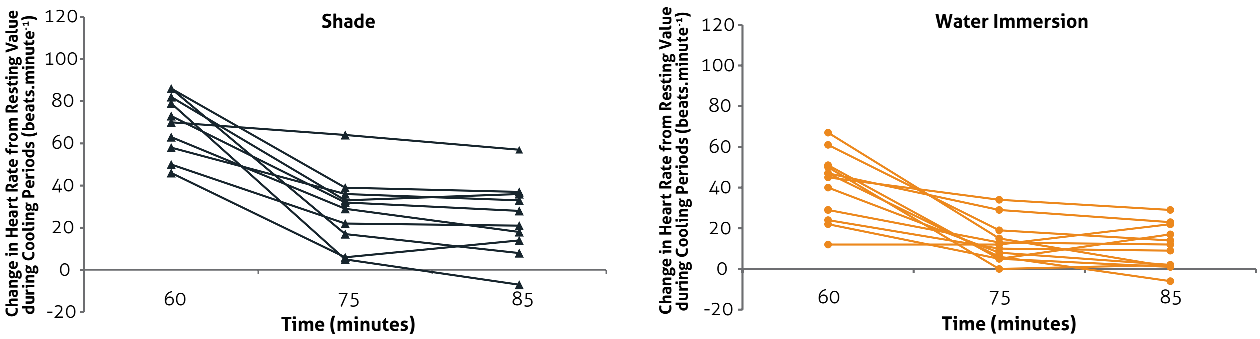
As evidenced by Figure 23, the misting fan and water immersion cohort heart rates were lower than the shade and ice ingestion groups. The misting fan and the water bath are considered to have lowered skin temperature that would decrease cutaneous blood flow (Pergola et al., 1993), requiring a smaller proportion of blood to be diverted to the skin for cooling. In turn, a lower heart rate is required to satisfy blood demand for cooling and perfusion. Peripheral vasoconstriction in the misting fan group was thought to limit the effectiveness of the cooling method in this study. Similar heart rate values despite a different core temperature response highlights the fact that heart rate alone cannot be used as a sole surrogate marker of core temperature change. The core cooling conferred by water immersion is likely to have also exerted a direct influence on heart rate due to cooler blood perfusing the heart of ~5 beats per minute (Jose et al., 1970; Rubin, 1987).

Figure 23. *Response of heart rate during the cooling phases*



The influence of temperate water immersion is demonstrated by Figure 24, with heart rate lower at the start, 15th and 25th minute of the second cooling phase compared to the shade group. A comparison of the Figure 24 shows a wider spread of individual heart rate responses and a generally elevated heart rate in the shade cohort. Note the plateauing of heart rate between 15 and 25 minutes for the shade cohort despite the core temperature drop shown in Figure 20.

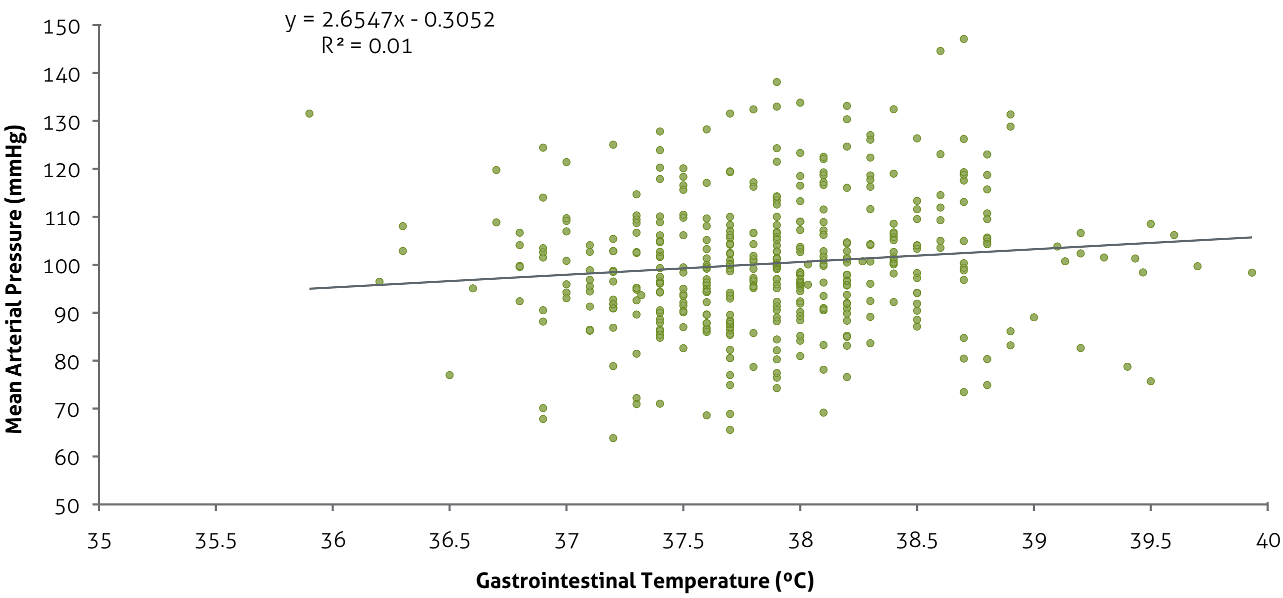
Figure 24. *Response of heart rate for shade (Δ) and water immersion (o) cohorts during the second cooling phase*



3.5.4. Blood Pressure

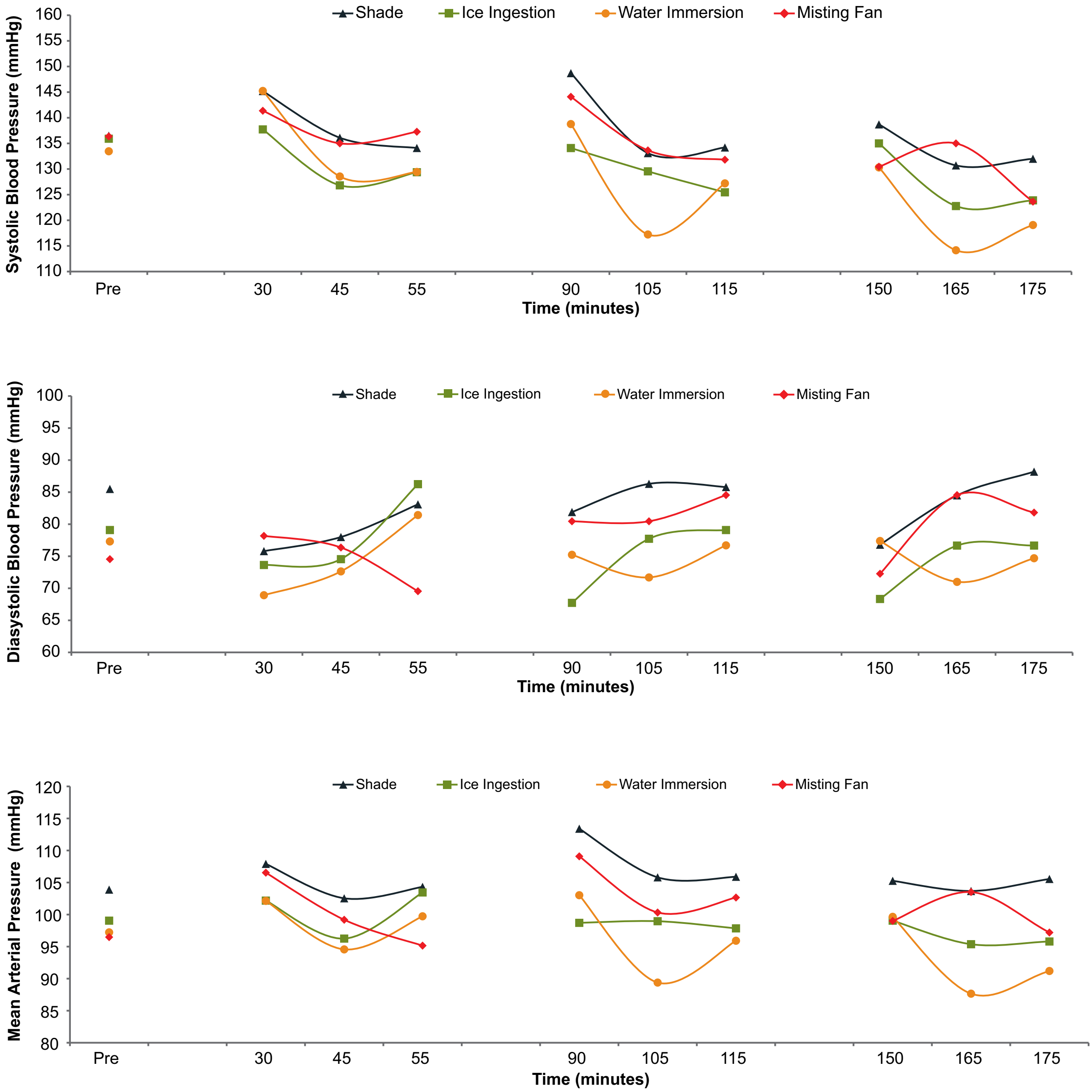
The low r value (0.12) of Figure 25 infers that mean arterial pressure has a poor correlation with gastrointestinal temperature. For example, candidates with a core temp of 35.9ºC had a mean arterial pressure of 131.5mmHg, while others with a temperature of 38.7ºC had mean arterial pressures ranging from 73.4 to 147.1mmHg.

Figure 25. *Scatterplot of gastrointestinal temperature and mean arterial pressure during the cooling phases (n=421 observations)*



Comparing the three graphs of Figure 26 representing the respective diastolic, systolic and mean arterial blood pressures highlights blood pressure as not useful in monitoring core temperature. It is not considered a good surrogate marker, nor is it considered useful to check in the rehabilitation monitoring of fire fighters as a routine. It should still be used for normal medical assessment of fire fighters who are injured or require medical attention for collapse from any cause. Physiological homeostasis of blood pressure is well controlled, and we expect blood pressure to remain relatively constant over long periods due to compensatory mechanisms of vasoconstriction or dilation, and increased or decreased heart rates and heart stroke volume.

Figure 26. *Response of systolic, diastolic and mean arterial pressure to the three cooling phases*



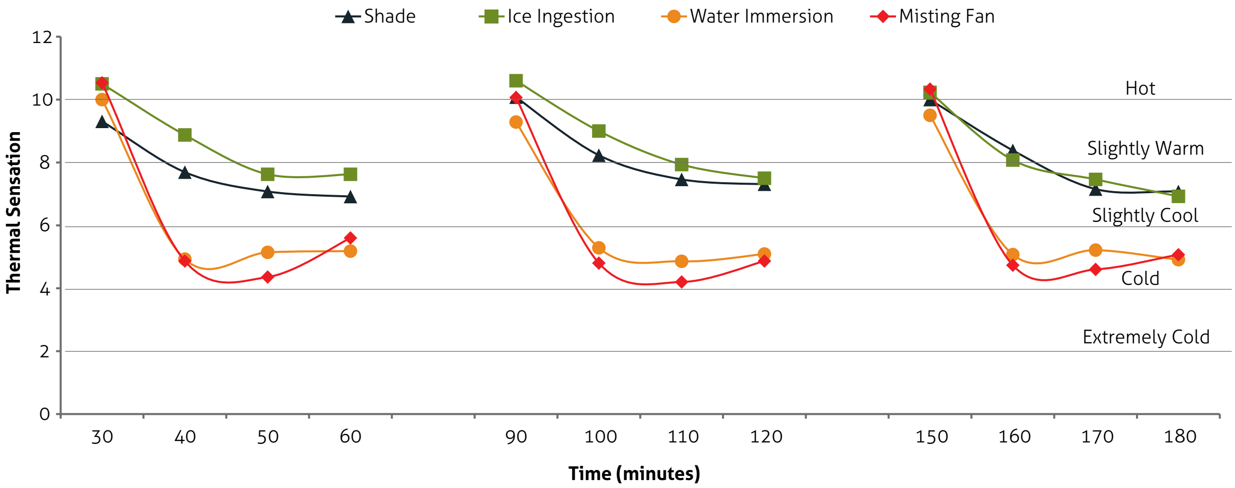
3.5.5. Thermal Sensation

KEY POINT Thermal sensation of very hot and very, very hot was associated with a core temperature of 38.5°C.

Thermal sensation was similar across all groups at the cessation of the work phases, attaining ratings of warm to hot (Figure 27.). This occurred despite differing core temperatures and varied environmental conditions on different days and is likely due to the similar microclimate within the protective clothing amongst the cohorts, resulting in high skin temperatures. Whereas core temperature is the key physiological variable determining sweating and skin blood flow responses to physical activity (Wyss et al., 1974), thermal sensation is derived with approximately equal input from core and peripheral temperature receptors (Frank et al., 1999), hence skin temperature plays a major role in determining a fire fighters thermal comfort.

The thermal sensation response to cooling was characterised by either a rapid (water immersion; misting fan) or a steady (shade; ice ingestion) response to the initial 10 minutes of cooling. A specific discussion of the thermal sensation response to the cooling mode follows in the proceeding sections.

Figure 27. *Response of thermal sensation throughout the cooling phases*



3.5.5.1 Shade and Ice Ingestion

Thermal strain was perceived as hot following each work period improving to attain a slightly warm rating 20 minutes into the cooling phase for the shade (Figure 28) and ice ingestion (Figure 29) cohorts. We anticipated a steeper improvement in thermal sensation during the initial 10 minutes of ice ingestion, based upon the results attained by athletes (Ihsan et al., 2010; Siegel et al., 2010, Ross et al., 2010) in a rested state. As denoted previously, the ice ingestion cohort's inability to consume the required volume of ice in a timely manner limited the cooling effect.

Figure 28. *Shade cohort's perception of thermal sensation throughout the cooling phases*

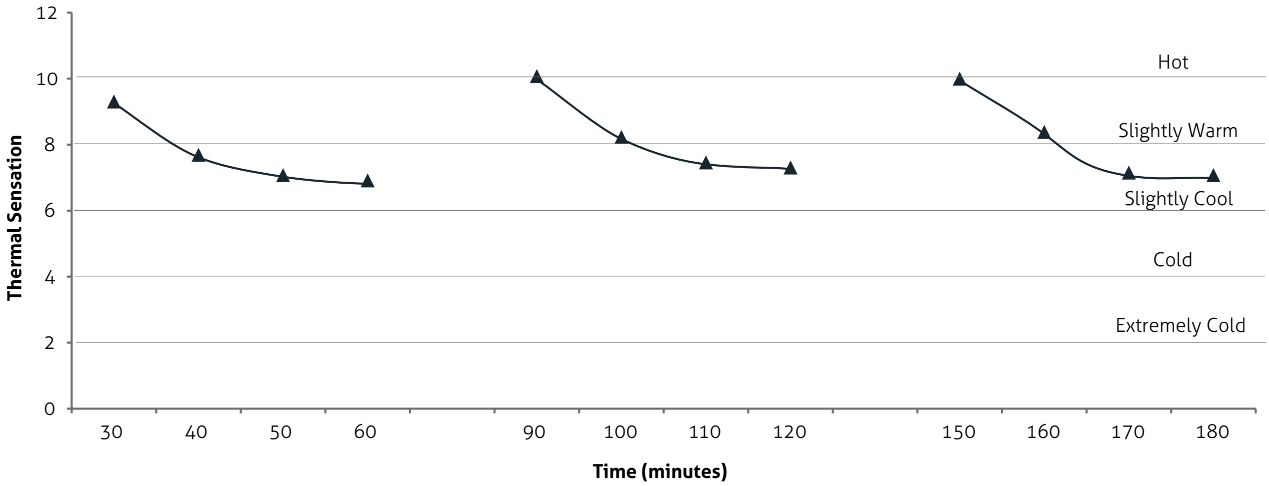
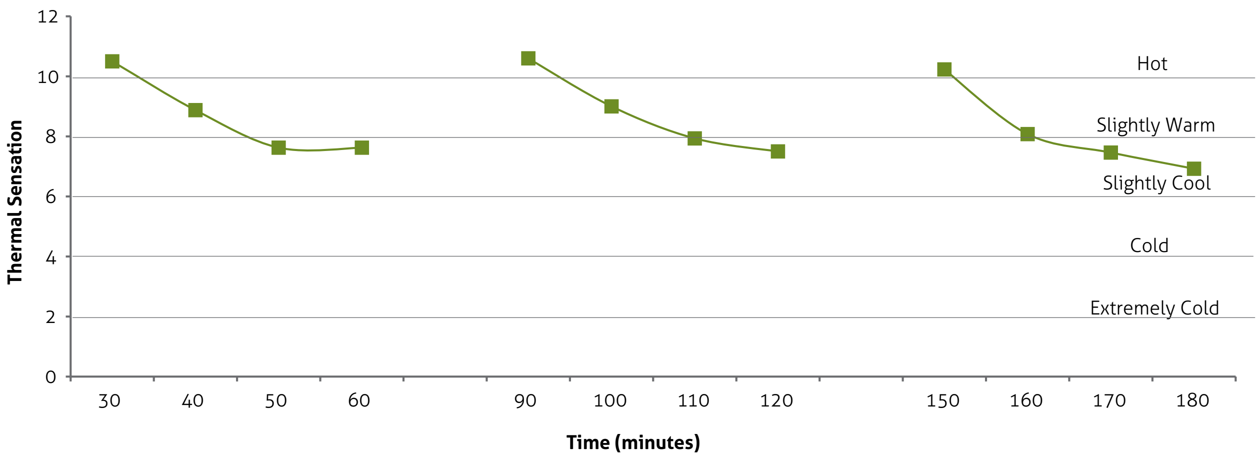
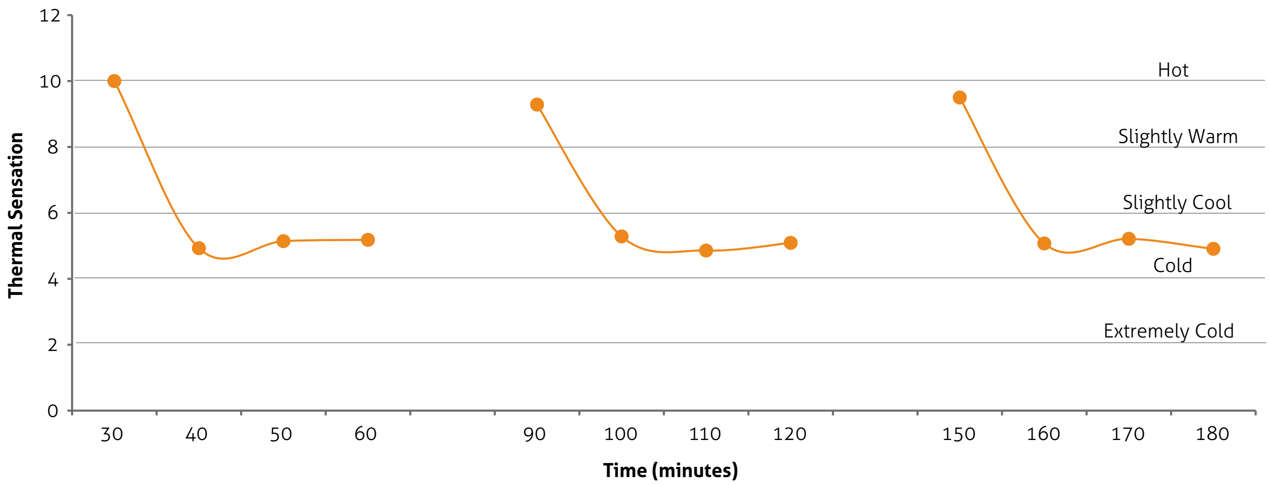


Figure 29. *Ice ingestion cohort's perception of thermal sensation throughout the cooling phases*



3.5.5.2. Water Immersion and Misting Fan

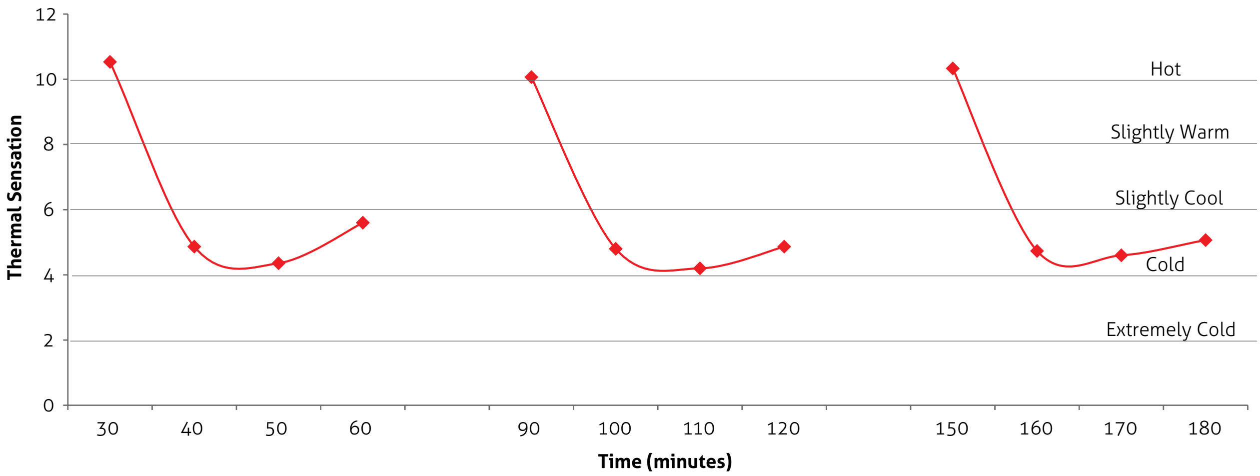
Figure 30. *Water immersion cohort's perception of thermal sensation throughout the cooling phases*



Ten minutes of water immersion was sufficient to attain an improvement of thermal sensation from hot to cool during each of the 3 cooling phases (Figure 30). The plateau of thermal sensation observed during the final 20 minutes of each cooling bout was expected, given that skin temperature is clamped at or near water temperature (25°C) during the immersion period. The perceptual results from the water bath are considered ideal as subjects felt cool at each measurement point with many positive comments. District Officer Rob Trewartha commented 'the rehab ice bath quickly renewed my energy level and the ability to remain focused. The third consecutive drill in BA was easier than the first'.

Immersion in 25°C waster was insufficient to attain ratings of cold, thereby limiting the likelihood of shivering.

Figure 31. *Misting Fan cohort's perception of thermal sensation throughout the cooling phases*



The misting fan produced a rapid alteration of thermal sensation from hot/very hot to cool at 10 minutes and to cold after 20 minutes (Figure 31). Thereafter, thermal sensation improved to attain a rating of cool/slightly cool. The degree of the thermal sensation response was not anticipated and caused many participants to cease cooling or to take a break from cooling. Unfortunately, the thermal sensation response did not translate into a beneficial core temperature decrease compared to the shade cohort. As discussed in 3.3.3., a cool periphery results in similar thermal sensation pattern as the water immersion group, without the core temperature decrease (due to peripheral vasoconstriction as noted on page 29). This highlights the disparity between thermal sensation and core temperature when subjects experience intense peripheral cooling via methods that lack overall cooling capacity (including ice jackets). Therefore, feedback from fire fighters cannot be relied upon under such circumstances to manage their exposure times during an incident.

3.5.6. Prediction of Core Temperature

Figure 32. *Scatterplot of gastrointestinal temperature and thermal sensation during the cooling phases (n=508 observations)*

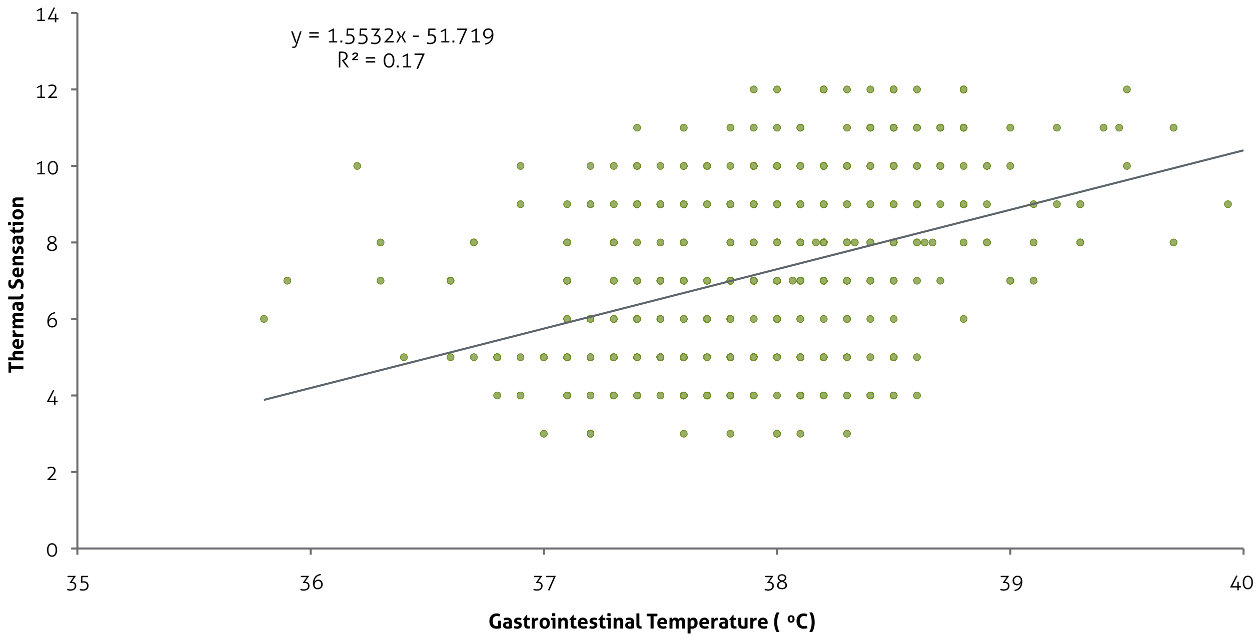


Figure 32 depicts the moderate correlation between gastrointestinal temperature and thermal sensation, a slightly weaker relationship than observed for heart rate (Section 3.5.2.). The value of thermal sensation as the simple surrogate for gastrointestinal temperature is therefore limited to stratifying thermal sensation with corresponding core temperatures (Table 13). The 42 occasions that thermal sensation was very hot or very, very hot occurred immediately after the work period (36) or 10 minutes into the cooling period (6) coincided with an average gastrointestinal temperature of 38.5°C. We recommend that NT Fire Fighters rate their thermal sensation prior to re-entry with those fire fighters rating very hot or above to continue their recovery with appropriate monitoring.

Table 13. *Distribution of thermal sensation and equivalent core temperatures. Data are mean (SD)*

Thermal Sensation Band	Mean Core Temperature (°C)	n
<7 (Neutral or Less)	37.7 (0.5)	210
7–8 (Neutral – Slightly Warm)	38.0 (0.6)	136
9–10 (Warm – Hot)	38.1 (0.6)	119
>10 (Very Hot or Above)	38.5 (0.5)	42

3.5.7. Surrogate Markers of Core Temperature Summary

The following checklist summarises the surrogate marker recommendations of this report. Tympanic temperature and blood pressure are not suitable substitutes for core temperature while heart rate and thermal sensation can be used in conjunction to manage fire fighters during an incident according to Table 14.

Table 14. *Summary of the surrogate markers for core temperature*

PHYSIOLOGICAL VARIABLE	USE	CRITERIA
Tympanic Temperature	✗	-
Blood Pressure	✗	-
Heart Rate	✓	Exclude if >120 beats.min^{-1}
Thermal Sensation	✓	Exclude if > 10 (Very Hot or above)

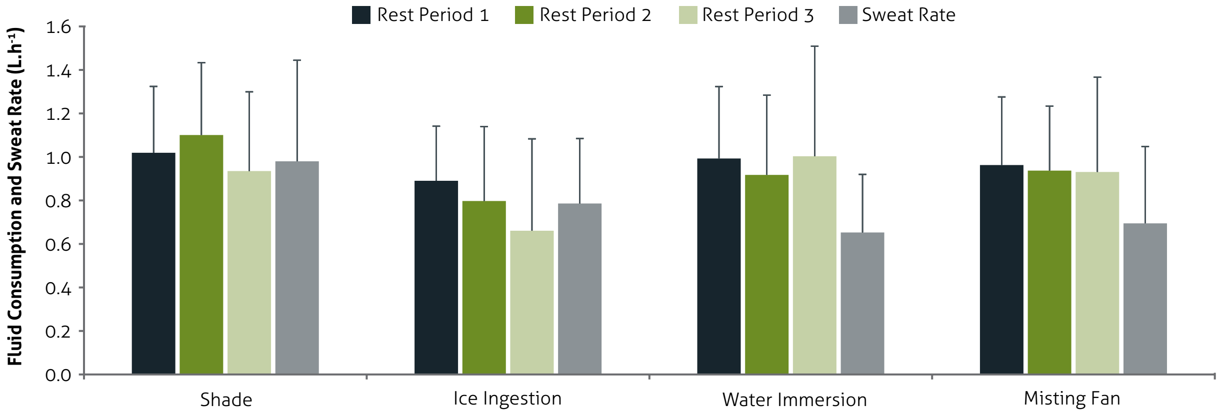
3.6. Fluid Balance

3.6.1. Fluid Consumption

KEY POINT Fluid consumption cannot be relied upon as the sole indicator of, or remedy to counteract heat storage.

Average fluid consumption was similar among the shade, water immersion and misting fan cohorts during each of the 3 cooling phases, ranging between 0.92 and 1.10 litres (Figure 33). While the crushed ice group ingested a similar volume during the initial cooling phase (0.89 litres), thereafter a substantial decrease was observed with 0.80 and 0.66 litres consumed during the second and third cooling periods respectively. Overall, total mean fluid consumption for the shade, ice ingestion, water immersion and misting fan cohorts was 3.06; 2.35; 2.91; 2.83 litres (1.02; 0.78; 0.97; 0.94 litres per hour) respectively. The similar fluid consumption between the shade, water immersion and misting fan groups occurred irrespective of the differences in core temperature, highlighting that fluid consumption cannot be relied upon as the sole indicator of, or remedy to counteract heat storage.

Figure 33. *Mean fluid consumption during the three rest phases referenced against sweat rate. Error bars represent SD.*



Excluding the ice ingestion cohort, the observed fluid intake rates are considered high bearing in mind that the fire fighters had slightly less than 30 minutes of each hour to drink, establishing that on average NT fire fighters can consume ~1L per hour with an equal work to rest ration. The provision of individual 1.5L drink bottles containing the fire fighters choice of fluid at the start of each cooling phase is a factor that could have contributed to the high rate of fluid consumption, as palatability improves beverage ingestion (Maughan et al., 1997) while hindering access to fluids has the opposite effect (Bergeron et al., 1995; Broad et al., 1996). It's intuitive to expect fluid consumption to decrease if the recommended 30 minutes of work to 20 minutes of rest is adopted, as time to available to drink would diminish by 33%. We also expect fluid consumption to decrease if fire fighters are not given ready access to fluids during breaks.

As previously discussed, the misting fan would have lowered skin temperature to mediate a local reduction of sweat rate. The 19.4% decrease of sweat rate with ice ingestion is greater than the 7.9% decrease reported by Siegel et al. (2010) where subjects sustained exercise for longer and tolerating a higher core temperature than subjects ingesting 4°C fluids. It should be noted that sweat rates can vary greatly depending upon the duties and environmental conditions in which they are performed. An example is provided by Hendrie et al. (1997) where average sweat rates ranged from 0.19 to 1.14L.h^{-1} for fire fighters in the field. We imposed the additional variable of cooling mode, such that the reported sweat rates are the product of HAZMAT containment, salvage operations, confined space operations, warm tropical conditions and cooling. Sweat rates for specific fire fighter duties in tropical field conditions remain to be quantified.

3.6.2. Sweat Rate

KEY POINT 30 minutes of 25°C water immersion limited sweat rate to 0.65 litres per hour, 33% lower than the shade cohort.

Figure 30 summarises the average sweat rates of the respective cohorts referenced against fluid consumption of each rest period. Temperate water immersion resulted in the lowest sweat rate of 0.65L.h^{-1}, 33.4% below the shade cohort's sweat rate of 0.98L.h^{-1}. A depressed sweat rate is commonly observed following temperate water immersion (Brearley and Finn, 2006; Kay et al., 1999; Wilson et al., 2002) with the lower core and skin temperatures probably delaying the onset of sweating once turnout gear was applied, as opposed to altering the core temperature at which sweating commences (White et al., 2003; Wilson et al., 2002).

3.6.3. Dehydration

KEY POINT Abbreviating recovery time is likely to promote dehydration, especially where combined with limited access to fluids.

With average fluid consumption of 0.97L.h^{-1} compared to an average sweat rate of 0.65L.h^{-1}, the water immersion cohort replaced 149% of sweat losses and gained ~1.0% body mass during the exercise, with a ~0.8% gain for misting fan and ~0.1% gain for the shade group (Table 13). Replacing 149% of sweat losses during physical activity is not common, with most investigations of athletes, fire fighters and soldiers reporting fluid consumption equates to 60–70% of sweat losses (Hendrie et al., 1997; Greenleaf, 1992; Nolte et al., 2010). Even the control group of this investigation that sat in the shade during rest periods prevented dehydration, precisely matching their sweat rate with ad libitum fluid consumption. The explanation for body mass gain of the cooling cohorts of this investigation is likely the culmination of lower sweat rates as a result of cooling; ready access to fluids of choice; the subjects' physical training and work experience in tropical conditions; and the hydration status upon commencement of the study. Overall the fire fighters did well to negate dehydration as a primary factor contributing to physiological strain, with the modest body mass gain observed for the ice ingestion, water immersion and misting fan cohorts unlikely to have mediated any benefit for the fire fighters (McLellan et al., 1999b; Dugas et al., 2009). The lack of a meaningful correlation between peak core temperature and dehydration (r=0.18) supports the notion that dehydration was not the primary determinant of heat storage in this study (Nolte et al., 2010), rather a factor that was mitigated by the hydration practices of all groups.

KEY POINT Fire fighters need to limit body mass losses to less than 2% body mass.

The threshold of ~2% body mass loss exists for endurance performance in compensable conditions and while such a threshold has not been stringently examined in uncompensable environments, 2.5% dehydration results in premature exhaustion regardless of work intensity and is detrimental to physiological responses at low work rates (Cheung and McLellan, 1998). Therefore, we recommend that fire fighters minimise body mass losses to less than 2% body mass.

3.6.4. Hydration Status

The lower fluid consumption of the crushed ice group coincided with the largest change in the pre and post USG values (1.014 to 1.024), such that despite commencing the simulation with the most favourable hydration status, the ice ingestion group finished the exercise with the least favourable hydration status despite the subjects maintaining their body mass (Table 15). This cohort was required to consume the crushed ice prior to accessing additional fluids, potentially limiting their fluid consumption and resulting in the maintenance of their body mass from pre to post-exercise. Ad libitum fluid consumption was adequate to maintain hydration status of Australian and American fire fighters during the 2009 'Black Saturday' suppression and recovery operations (Raines et al., 2009). In that study the fire fighters averaged a similarly dehydrated pre-shift USG of 1.019 to the findings of our investigation (Table 16). Analogous pre-shift USG values of 1.016 and 1.019 have also been observed for professional wildland fire fighters (Cuddy et al., 2008; Ruby et al., 2003); while 91% of professional structural fire fighters have exceeded a USG of 1.010 (Espinosa, 2008).

Table 15. *Change in Body Mass during the Protocol. Data are Mean (SD).*

Cohort	Gain/Loss	Body Mass Change (kg)	Body Mass Change (%)
Shade	Gain	0.12 (1.35)	0.22 (1.73)
Ice Ingestion	Loss	0.01 (0.61)	0.03 (0.73)
Water Immersion	Gain	0.95 (0.91)	1.11 (1.06)
Misting Fan	Gain	0.75 (1.16)	0.87 (1.35)

Pre-hydration status also influences physiological strain during uncompensable heat stress (Cheung and McLellan, 1998). Commencing a work bout in a well hydrated state provides a buffer to developing dehydration, particularly where fluids are not as freely available as in the current investigation. So while attention could solely be focused on hydration during the work period, we recommend that fire fighters ensure they are well hydrated/ minimally dehydrated prior to work, limiting the likelihood of developing 2% dehydration throughout their shift. Dehydration at rates less than 2% are unlikely to have any deleterious effects on physiological parameters or work rate. Fire fighters, like athletes, find it difficult to properly assess their hydration status. Use or urine colour charts may help to a certain extent, but weight gain or loss prior to and during the incident is the most effective method of documenting large losses in body fluid. Use of body mass scales at protracted incidents would be a useful addition to current practice.

Table 16. *Change in Body Mass during the Protocol. Data are Mean (SD).*

Cohort	Pre USG	Post USG	USG Difference
Shade	1.016 (0.008)	1.022 (0.004)	0.006
Ice Ingestion	1.014 (0.009)	1.024 (0.006)	0.010
Water Immersion	1.018 (0.006)	1.018 (0.007)	0.000
Misting Fan	1.021 (0.007)	1.025 (0.007)	0.004

3.6.5. Fluid Balance Summary

Overall, the fire fighters were mildly to significantly dehydrated prior to the exercise and consumed adequate fluids to maintain or slightly increase their body mass. Improvements in pre-exercise/shift hydration would provide a greater defence to the development of significant dehydration, particularly where fluids are not as accessible. Ingesting a pre-shift bolus of fluid would improve hydration status, but may reduce ad libitum consumption as the drive to drink is diminished, resulting in similar overall consumption (Raines et al., 2009). Regardless, pre-shift hydration provides fire fighters with a margin of safety for developing dehydration that may be utilised where an incident doesn't allow adequate fluid consumption. Linking pre-shift fluid consumption guidelines to the prevailing Fire Danger Index (FDI) would recommend higher fluid consumption when the likelihood of response (and therefore restricted access to fluids) is greater. Recent personal experience from the Australian medical assistance team (AusMAT) mission to flood relief in Pakistan September 2010 (working under a joint AusAID/Australian Defence Force task force) have indicated the value of pre-work hydration boluses in austere conditions (39°C maximum, 30°C minimum ambient temperature). Dehydration was minimised in the civilian medical team in particular with the use of three times daily weight measurements and a pre-shift fluid bolus recommendation of 15mL.kg^{-1} body mass during the first week of deployment.

Cooling via 25°C water immersion lowers sweat rate and where combined with free access to fluids are likely to limit the development of dehydration greater than 2% body mass. Educating fire fighters in this regard is recommended with the assessment of individual sweat rates during training sessions a catalyst to provide fire fighters with an indication of fluid requirements during dry and wet season conditions. Providing body mass scales at the station and in the rehabilitation centre at a protracted incident is necessary to achieve this objective. Educating fire fighters on their day to day body mass and having this recorded for use by those assessing fire fighters in the field rehabilitation unit at protracted incidents is a key recommendation.

With similar fluid balance among the cohorts and prevention of 2% body mass loss, work rate and cooling were the key factors determining the core temperature response during this investigation.

4. Key Recommendations

4.1. Rehabilitation Centre

- Fire and Rescue Services should consider a review into the rehabilitation of its personnel at protracted incidents or training exercises. For protracted incidents (>1 hour duration or requiring 2 breathing apparatus cylinder changes) that demand strenous workloads,we recommend establishment of a rehabilitation centre. The rehabilitation centre must be shaded and screened from public view with a single entry and exit point as depicted by Figure 34.

4.2. Cooling – Incidents > 1 hour

That fire fighters undertake 15 minutes of 25°C water immersion following ~30 minutes of response or equivalent to one cylinder change, were strenous workloads are encounted.

That a high speed fan provide an evaporative cooling option within the rehabilitation centre.

Figure 34. *Schematic of proposed rehabilitation centre.*

Water Immersion – adequate water immersion for 6 fire fighters, with water temperature of 25°C.

Fan – High speed floor fan to provide adequate air movement to cool 9 fire fighters.

Medical Monitoring Area – incorporating measurement of heart rate, thermal sensation and monitoring for physical signs of heat exhaustion.

Hydration Station – provide access to water and a carbohydrate/electrolyte beverage, both served at ~15°C.

- Fire and Rescue Services should consider a review into their policy and procedures regarding heat related illnesses. Ongoing reviews should be considered to reflect technology advancements and future research.
- Establishment of such a rehabilitation centre requires medical support. Therefore, Fire and Rescue Services should consider a review into provision of appropriate medical services at incidents or training exercises which have a likelihood of exposing personnel to conditions that are predisposed to producing heat related illnesses.

4.3. Hydration

- Education of fire fighters to improve pre-shift/incident hydration status. Fire fighters should recognise that where access to fluids is restricted, improving hydration status provides a margin of safety for development of dehydration.

- Linking pre-shift/incident hydration status to the prevailing Fire Danger Index (FDI) should be considered. This initiative would associate fluid consumption with the likelihood of restricted access to fluids during incident response.

- Education of fire fighters to minimise body mass loss to less than 2% (1.7kg for an 85kg fire fighter) during incidents and/or shifts. Assessment of fluid balance during daily activities would assist fire fighters to understand their fluid requirements in a practical setting. This should include regular assessment and recording of body mass for use by those assessing fire fighters in the field rehabilitation unit.

- Fluids should be readily available during incidents and served at a temperature of ~15°C. Fire fighters ought to have the option of water and a carbohydrate/electrolyte beverage to cater for individual preferences.

4.4. Surrogate Markers

- Fire fighters achieve a heart rate of less than 120 beats.min^{-1} prior to re-entering an incident.

- Fire fighters rate their thermal sensation according to Appendix 7.2, and achieve a rating of 10 (hot) or less prior to re-entry.

4.5. Equipment

That fire service vehicles including Grass Fire Units and tankers have their water tanks modified to permit emergency cooling of fire fighters until a rehabilitation sector can be established.

Consideration should be given to linking pre-shift fluid consumption guidelines and the prevailing Fire Danger Index.

5. Acknowledgements

5.1. Contributors

National Critical Care and Trauma Response Centre (NCCTRC)

Provided monetary and administrative support for this project including supply of core temperature pills, medical equipment and some catering and related expenses. The NCCTRC employs several of the lead authors of this report. The NCCTRC provided staff and administrative support during the write up phase of this report, as well as covering all costs of report publication and distribution

Northern Territory Institute of Sport (NTIS)

Staff and equipment were provided without charge by NTIS to each of the trials, with multiple volunteers from NTIS involved, including one of the lead authors of this report. Preparation and equipment checking phases occurred at the NTIS laboratory, as did urine testing and some data management post trial. Equipment including much of the physiological monitoring devices and biometric testing equipment were supplied at no cost by NTIS.

Northern Territory Fire and Rescue Services (NTFRS)

With support from NTFRS management, the Stuart Park facility, including offices, engine bays and fire training areas was made available. Many fire fighters were involved in the project, in particular one of the lead authors. Fire fighters taking part in the study as subjects and support staff were volunteers throughout the trial periods, with insurance and other cover provided by NTFRS as if "on-shift". Various equipment hardware and all fire-fighting equipment and uniforms were provided free of charge by NTFRS.

Medical Staff and Students

During the course of data collection and field trials, staff and medical students from the Royal Darwin Hospital (RDH) volunteered their time. This included all aspects of preparation, data recording and medical coverage during the many field trials. Medical response equipment was sourced from both the RDH and NCCTRC for this medical cover.

Fire Fighters

As stated above, all fire fighters were voluntarily involved in the series of trials as subjects and safety and assistance officers. Most gave up to a whole day per trial, many over successive trials, without pay. Several travelled from remote stations to be involved. Without their enthusiasm, and willingness to endure discomfort, this trial would not have been possible. Their contribution to the health and safety of their colleagues by taking part in the study is applauded.

5.2. Competing Interests

The research team members have no financial interest in any of the products utilised in the conduct of this research. The NCCTRC did not receive sponsorship from any organisation in relation to this research.

5.3. Author Profiles

Dr Matt Brearley is the Disaster Medical Research Program Manager of the NCCTRC, formerly holding the position of Athlete Services Manager at the Northern Territory Institute of Sport, Darwin. Matt earned a PhD in thermal physiology from Charles Darwin University in 2006 studying responses of athletes competing in the tropics and developing pre-cooling protocols. Matt has worked with elite junior and senior athletes to maximise their performance in the heat and was the heat specialist of the Australian team during the 2008 Olympic Games in Beijing, China.

Dr Ian Norton a specialist emergency physician with additional post graduate qualifications in tropical medicine, international health and surgery. He is the director of disaster preparedness and response at the NCCTRC. He led the medical team response to the Ashmore Reef boat explosion and also led the civilian medical team during the combined AusAID/ADF joint task force response to the Pakistan floods Aug-Oct 2010 in a remote area of the Punjab region in hot conditions. Ian leads AusMAT Northern Territory as well as working nationally on the AusMAT working group with particular focus on heat specific uniforms and equipment, and leads NCCTRC educational elements including remote area trauma education, AusMAT local, national and international courses, and is national director of MIMMS Australia (Major Incident Medical Management and Support).

Station Officer Terry Trewin is attached to the operations section of the NTFRS based in Darwin. Terry has qualifications in Emergency Management, Applied Science and Pre-hospital Emergency Care. Terry is also an emergency response consultant to the NCCTRC. Terry has a long proactive history for the rehabilitation of emergency responders at incidents and delivering pre hospital emergency care in the Northern Territory.

Dr Clare Mitchell is an advanced trainee with the Australian College of Emergency Medicine and was formerly a retrieval registrar with the Northern Territory Aeromedical Service. She has a postgraduate diploma in Tropical Medicine and public health.

5.4. About the National Critical Care and Trauma Response Centre

The NCCTRC is a federally funded organization based at Royal Darwin Hospital (RDH). The Department of Health and Ageing (DOHA) provide this support to the NT Department of Health and the NCCTRC in recognition of previous responses to events such as the first and second Bali bombing, the Timor Leste unrest and responses to various northern Australian mass casualty events such as the Ashmore Reef refugee boat explosion. Recent deployments include the Boat explosion, and provision of the leadership, and largest proportion of civilian medical responders, and their personal response equipment, to the AusAID and Australian Defence Force joint mission to flood relief in Pakistan. This has confirmed the NCCTRC 's role in provision of a ready response medical team for the Northern Australian region.

The NCCTRC is tasked to enhance the capability of the RDH to respond to health events of national significance when tasked by the national incident room of DOHA, and to provide medical response teams when required. It provides a trauma patient management service for day to day operations in the RDH, as well as assisting in various other parts of the hospital with equipment and additional staff.

The NCCTRC has a regional and national role in preparedness, research and education. It leads several national disaster and trauma courses, as well as providing multiple trauma and related health courses for local staff. It has a key role in developing research in the areas of disaster preparedness, response and trauma. Heat trials in responders wearing CBRN (Chemical Biological Radiological and Nuclear) resistant suits, coupled with this series of trials are the first of several heat related trials planned at the centre. Work and initial trials have commenced on Australian Medical Assistance Teams (AusMAT) wearing tropical climate uniforms, and their physiological responses to work in the field during medical missions. The research programme also includes major projects such as the national disaster health capability audit for 2011 and for the development of a national bar-code tracking system for patients and evacuees during times of disaster. Multiple other research projects are ongoing covering novel approaches to the treatments and monitoring of mass casualties, burns and infectious disease patients during times of disaster, as well as hospital based studies related to our extensive trauma database. For more information see www.nationaltraumacentre.nt.gov.au.

6. References

- Adams WC, Fox RH, Fry AJ, MacDonald IC (1975). Thermoregulation during marathon running in cool, moderate, and hot environments. Journal of Applied Physiology 38, 1030-7
- Amoateng-Adjepong Y, Del Mundo J, Manthous CA (1999). Accuracy of an infrared tympanic thermometer. Chest 115(4), 1002-5
- Armstrong LE, Crago AE, Adams R, Roberts WO, Maresh CM (1996). Whole-body cooling of hyperthermic runners: comparison of two field therapies. American Journal of Emergency Medicine 14(4), 355-8
- Arngrïmsson SA, Petitt DS, Stueck MG, Jorgensen DK, Cureton KJ (2004). Cooling vest worn during active warm-up improves 5-km run performance in the heat. Journal of Applied Physiology 96(5), 1867-74
- Aoyagi Y, McLellan TM, Shephard RJ (1994). Effects of training and acclimation on heat tolerance in exercising men wearing protective clothing. European Journal of Applied Physiology and Occupational Physiology 68(3), 234-45
- Barr D, Gregson W, Sutton L, Reilly T (2009). A practical cooling strategy for reducing the physiological strain associated with firefighting activity in the heat. Ergonomics 52(4), 413-20
- Bennett BL, Hagan RD, Huey KA, Minson C, Cain D (1995). Comparison of two cool vests on heat-strain reduction while wearing a firefighting ensemble. European Journal of Applied Physiology and Occupational Physiology 70(4), 322-8
- Bergeron MF, Maresh CM, Armstrong LE, Signorile JF, Castellani JW, Kenefick RW, LaGasse KE, Riebe DA (1995). Fluid-electrolyte balance associated with tennis match play in a hot environment. International Journal of Sport Nutrition 5(3), 180-93
- Brearley MB, Finn JP (2003). 'Pre-cooling for Performance in the Tropics'. Sportscience Perspectives: Training and Performance. Available at http://www.sportsci.org/jour/03/mbb.htm
- Brearley M, Finn JP (2006). Physiological, perceptual and performance responses to intermittent high intensity activity in a tropical environment following pre-cooling. Proceedings of the 2nd Australian Association of Exercise and Sport Science Conference and the 4th Sport Dieticians Australia Update. Sydney, September – October, p.48
- Brearley MB, Finn JP (2007). Responses of motor-sport athletes to V8 supercar racing in hot conditions. International Journal of Sports Physiology and Performance 2(2), 182-91
- Broad EM, Burke LM, Cox GR, Heeley P, Riley M (1996). Body weight changes and voluntary fluid intakes during training and competition sessions in team sports. International Journal of Sport Nutrition 6(3), 307-20
- Burdon C, O'Connor H, Gifford J, Shirreffs S, Chapman P, Johnson N (2010). Effect of drink temperature on core temperature and endurance cycling performance in warm, humid conditions. Journal of Sports Sciences 28(11), 1147-56
- Cadarette BS, Levine L, Kolka MA, Proulx GN, Correa MM, Sawka MN (2002). Heat strain reduction by ice-based and vapor compression liquid cooling systems with a toxic agent protective uniform. Aviation Space and Environmental Medicine 73(7), 665-72
- Cadarette BS, Levine L, Staab JE, Kolka MA, Correa MM, Whipple M, Sawka MN (2003). Upper body cooling during exercise-heat stress wearing the improved toxicological agent protective system for HAZMAT operations. American Industrial Hygiene Association Journal 64(4), 510-5
- Carter JM, Rayson MP, Wilkinson DM, Richmond V, Blacker S (2007). Strategies to combat heat strain during and after firefighting. Journal of Thermal Biology 32(2), 109-116
- Casa DJ, Armstrong LE, Hillman SK, Montain SJ, Reiff RV, Rich BS, Roberts WO, Stone JA (2000). National Athletic Trainers' Association Position Statement: Fluid Replacement for Athletes. Journal of Athletic Training 35(2), 212-224
- Casa DJ, McDermott BP, Lee EC, Yeargin SW, Armstrong LE, Maresh CM (2007). Cold water immersion: the gold standard for exertional heatstroke treatment. Exercise and Sport Science Reviews 35(3), 141-9
- Cavanagh G (2005). Inquest into the death of Angus Lawrence NTMC 069. Available at http://www.nt.gov.au/justice/ntmc/judgements/documents/2005NTMC069.pdf
- Cheung SS, McLellan TM (1998). Heat acclimation, aerobic fitness, and hydration effects on tolerance during uncompensable heat stress. Journal of Applied Physiology 84(5), 1731-9
- Cheung SS, Montie DL, White MD, Behm D (2003). Changes in manual dexterity following short-term hand and forearm immersion in 10 degrees C water. Aviation, Space and Environmental Medicine 74(9), 990-3
- Christensen H, Boysen G (2002). Acceptable agreement between tympanic and rectal temperature in acute stroke patients. International Journal of Clinical Practice 56(2), 82-4
- Clements JM, Casa DJ, Knight J, McClung JM, Blake AS, Meenen PM, Gilmer AM, Caldwell KA (2002). Ice-Water Immersion and Cold-Water Immersion Provide Similar Cooling Rates in Runners With Exercise-Induced Hyperthermia. Journal of Athletic Training 37(2), 146-150
- Coutts AJ, Quinn J, Hocking J, Castagna C, Rampinini E (2010). Match running performance in elite Australian Rules Football. Journal of Science and Medicine in Sport 13(5), 543-8

- Cuddy JS, Ham JA, Harger SG, Slivka DR, Ruby BC (2008). Effects of an electrolyte additive on hydration and drinking behavior during wildfire suppression. Wilderness and Environmental Medicine 19(3), 172-80
- Desruelle AV, Candas V (2000). Thermoregulatory effects of three different types of head cooling in humans during a mild hyperthermia. European Journal of Applied Physiology 81(1-2), 33-9
- Ducharme MB, Tikuisis P (1991). In vivo thermal conductivity of the human forearm tissues. Journal of Applied Physiology 70(6), 2682-90
- Duffield R, Dawson B, Bishop D, Fitzsimons M, Lawrence S (2003). Effect of wearing an ice cooling jacket on repeat sprint performance in warm/humid conditions. British Journal of Sports Medicine 37(2), 164-9
- Duffield R, Steinbacher G, Fairchild TJ (2009). The use of mixed-method, part-body pre-cooling procedures for team-sport athletes training in the heat. Journal of Strength and Conditioning Research 23(9), 2524-32
- Dugas JP, Oosthuizen U, Tucker R, Noakes TD (2009). Rates of fluid ingestion alter pacing but not thermoregulatory responses during prolonged exercise in hot and humid conditions with appropriate convective cooling. European Journal of Applied Physiology 105(1), 69-80
- Espinosa N (2008). Can we stand the heat? Journal of Emergency Services 33, 94-105
- Frank SM, Raja SN, Bulcao CF, Goldstein DS (1999). Relative contribution of core and cutaneous temperatures to thermal comfort and autonomic responses in humans. Journal of Applied Physiology 86(5), 1588-93
- Galloway SD, Maughan RJ (1997). Effects of ambient temperature on the capacity to perform prolonged cycle exercise in man. Medicine and Science in Sports and Exercise 29(9), 1240-9
- Gagge AP, Stolwijk JA, Hardy JD (1967). Comfort and thermal sensations and associated physiological responses at various ambient temperatures. Environmental Research 1(1), 1-20
- Giesbrecht GG, Jamieson C, Cahill F (2007). Cooling hyperthermic firefighters by immersing forearms and hands in 10 degrees C and 20 degrees C water. Aviation Space and Environmental Medicine 78(6), 561-7
- Gonzalez-Alonso J, Teller C, Andersen SL, Jensen FB, Hyldig T, Nielsen B (1999). Influence of body temperature on the development of fatigue during prolonged exercise in the heat. Journal of Applied Physiology 86(3), 1032-9
- Gore CJ, Bourdon PC, Woolford SM, Pederson DG (1993). Involuntary dehydration during cricket. International Journal of Sports Medicine 14(7), 387-95
- Greenleaf JE (1992). Problem: thirst, drinking behavior, and involuntary dehydration. Medicine, Science in Sports and Exercise 24(6), 645-56
- Hasegawa H, Takatori T, Komura T, Yamasaki M (2005). Wearing a cooling jacket during exercise reduces thermal strain and improves endurance exercise performance in a warm environment. Journal of Strength and Conditioning Research 19(1), 122-8
- Heled Y, Epstein Y, Moran DS (2004). Heat strain attenuation while wearing NBC clothing: dry-ice vest compared to water spray. Aviation, Space and Environmental Medicine 75(5), 391-6
- Hendrie AL, Brotherhood JR, Budd GM, Jeffery SE, Beasley FA, Costin BP, Zhien W, Baker MM, Cheney NP, Dawson MP (1997). Project Aquarius 8. Sweating, drinking, and dehydration in men suppressing wildland fires. International Journal of Wildland Fire 7(2), 145-158
- Hostler D, Reis SE, Bednez JC, Kerin S, Suyama J (2010). Comparison of active cooling devices with passive cooling for rehabilitation of firefighters performing exercise in thermal protective clothing: a report from the Fireground Rehab Evaluation (FIRE) trial. Prehospital and Emergency Care 14(3), 300-9
- House JR, Lunt H, Magness A, Lyons J (2003). Testing the effectiveness of techniques for reducing heat strain in Royal Navy nuclear, biological and chemical cleansing stations' teams. Journal of the Royal Naval Medical Service 89(1), 27-34
- Ilmarinen R, Lindholm H, Koivistoinen K, Helistén P (2004). Physiological evaluation of chemical protective suit systems (CPSS) in hot conditions. International Journal of Occupational Safety and Ergonomics 10(3), 215-26
- Ihsan M, Landers G, Brearley M, Peeling P (2010). Beneficial effects of ice ingestion as a precooling strategy on 40-km cycling time-trial performance. International Journal of Sports Physiology and Performance 5(2), 140-51
- Jentjens RL, Wagenmakers AJ, Jeukendrup AE (2002). Heat stress increases muscle glycogen use but reduces the oxidation of ingested carbohydrates during exercise. Journal of Applied Physiology 92(4), 1562-72
- Johnson KG, Cabanac M (1983). Human thermoregulatory behaviour during a conflict between cold discomfort and money. Physiology and Behaviour 30(1), 145-50
- Jose AD, Stitt F, Collison D (1970). The effects of exercise and changes in body temperature on the intrinsic heart rate in man. American Heart Journal 79(4), 488-98
- Kay D, Taaffe DR, Marino FE (1999). Whole-body pre-cooling and heat storage during self-paced cycling performance in warm humid conditions. Journal of Sports Sciences 17(12), 937-44
- Khomenok GA, Hadid A, Preiss-Bloom O, Yanovich R, Erlich T, Ron-Tal O, Peled A, Epstein Y, Moran DS (2008). Hand immersion in cold water alleviating physiological strain and increasing tolerance to uncompensable heat stress. European Journal of Applied Physiology 104(2), 303-9

- Latzka WA, Sawka MN, Montain SJ, Skrinar GS, Fielding RA, Matott RP, Pandolf KB (1998). Hyperhydration: tolerance and cardiovascular effects during uncompensable exercise-heat stress. Journal of Applied Physiology 84(6), 1858-64
- Lee DT, Haymes EM (1995). Exercise duration and thermoregulatory responses after whole body precooling. Journal of Applied Physiology 79(6), 1971-6
- Lee JK, Shirreffs SM, Maughan RJ (2008). Cold drink ingestion improves exercise endurance capacity in the heat. Medicine and Science in Sports and Exercise 40(9), 1637-44
- Maughan RJ, Leiper JB, Shirreffs SM (1997). Factors influencing the restoration of fluid and electrolyte balance after exercise in the heat. British Journal of Sports Medicine 31(3), 175-82
- Marino F, Sockler JM, Fry JM (1998). Thermoregulatory, metabolic and sympathoadrenal responses to repeated brief exposure to cold. Scandinavian Journal of Clinical Laboratory Investigation 58(7), 537-45
- Maron MB, Wagner JA, Horvath SM (1977). Thermoregulatory responses during competitive marathon running. Journal of Applied Physiology 42(6), 909-14
- Maté, J., Siegel, R., Watson, G., Oosthuizen, J., Laursen, P (2010). Comparison of ad libitum drinking of liquid versus ice slurry solutions on core temperature during simulated mining conditions. Presented at the 15th Annual ECSS-Congress, Antalya
- McLellan TM, Frim J, Bell DG (1999a). Efficacy of air and liquid cooling during light and heavy exercise while wearing NBC clothing. Aviation, Space and Environmental Medicine 70(8), 802-11
- McLellan TM, Cheung SS, Latzka WA, Sawka MN, Pandolf KB, Millard CE, Withey WR (1999b). Effects of dehydration, hypohydration, and hyperhydration on tolerance during uncompensable heat stress. Canadian Journal of Applied Physiology 24(4), 349-61
- McLellan TM, Selkirk GA (2006). The management of heat stress for the firefighter: a review of work conducted on behalf of the Toronto Fire Service. Industrial Health 44(3), 414-26
- McDermott BP, Casa DJ, Ganio MS, Lopez RM, Yeargin SW, Armstrong LE, Maresh CM (2009). Acute whole-body cooling for exercise-induced hyperthermia: a systematic review. Journal of Athletic Training 44(1), 84-93
- Mier CM, Domenick MA, Turner NS, Wilmore JH (1996). Changes in stroke volume and maximal aerobic capacity with increased blood volume in men women. Journal of Applied Physiology 80(4), 1180-6
- Mittleman KD, Mekjavić IB (1988). Effect of occluded venous return on core temperature during cold water immersion. Journal of Applied Physiology 65(6), 2709-13
- Moran D, Epstein Y, Keren G, Laor A, Sherez J, Shapiro Y (1995). Calculation of mean arterial pressure during exercise as a function of heart rate. Applied Human Sciences 14(6), 293-5
- Muir IH, Bishop PA, Lomax RG, Green JM (2001). Prediction of rectal temperature from ear canal temperature. Ergonomics 44(11), 962-72
- Mündel T, King J, Collacott E, Jones DA (2006). Drink temperature influences fluid intake and endurance capacity in men during exercise in a hot, dry environment. Experimental Physiology 91(5), 925-33
- Myler GR, Hahn AG, Tumilty DM (1989). The effect of preliminary skin cooling on performance of rowers in hot conditions. Excel 6, 17-21
- Norton I, Brearley M, Trewin T, Hrabar K (2010). A comparison of novel cooling methods for prevention of hyperthermia in CBR responders in the 'Top End' of Australia. Technical Report.
- Nolte H, Noakes TD, Van Vuuren B (2010). Ad libitum fluid replacement in military personnel during a 4-h route march. Medicine and Science in Sports and Exercise 42(9), 1675-80
- Nielsen B, Hales JR, Strange S, Christensen NJ, Warberg J, Saltin B (1993). Human circulatory and thermoregulatory adaptations with heat acclimation and exercise in a hot, dry environment. Journal of Physiology 460, 467-85
- Nielsen B, Strange S, Christensen NJ, Warberg J, Saltin B (1997). Acute and adaptive responses in humans to exercise in a warm, humid environment. Pflugers Archives 434(1), 49-56
- Nybo L, Nielsen B (2001). Hyperthermia and central fatigue during prolonged exercise in humans. Journal of Applied Physiology 91(3), 1055-60
- O'Brien E, Beevers G, Lip GY (2001). ABC of hypertension: Blood pressure measurement. Part IV-automated sphygmomanometry: self blood pressure measurement. British Medical Journal 322(7295), 1167-70
- O'Brien C, Hoyt RW, Buller MJ, Castellani JW, Young AJ (1998). Telemetry pill measurement of core temperature in humans during active heating and cooling. Medicine and Science in Sports and Exercise 30(3), 468-72
- Ozgünen KT, Kurdak SS, Maughan RJ, Zeren C, Korkmaz S, Yazici Z, Ersöz G, Shirreffs SM, Binnet MS, Dvorak J (2010). Effect of hot environmental conditions on physical activity patterns and temperature response of football players. Scandinavian Journal of Medicine and Science in Sports Suppl 3:140-7
- Parkin JM, Carey MF, Zhao S, Febbraio MA (1999). Effect of ambient temperature on human skeletal muscle metabolism during fatiguing submaximal exercise. Journal of Applied Physiology 86(3), 902-8
- Patterson MJ, Warlters D, Taylor NA (1994). Attenuation of the cutaneous blood flow response during combined exercise and heat stress. European Journal of Applied Physiology and Occupational Physiology 69(4), 367-9

- Peiffer JJ, Abbiss CR, Nosaka K, Peake JM, Laursen PB (2009a). Effect of cold water immersion after exercise in the heat on muscle function, body temperatures, and vessel diameter. Journal of Science and Medicine in Sport 12(1), 91-6
- Peiffer JJ, Abbiss CR, Watson G, Nosaka K, Laursen PB (2009b). Effect of cold-water immersion duration on body temperature and muscle function. Journal of Sports Sciences 27(10), 987-93
- Peiffer JJ, Abbiss CR, Watson G, Nosaka K, Laursen PB (2010a). Effect of cold water immersion on repeated 1-km cycling performance in the heat. Journal of Science and Medicine in Sport 13(1), 112-6
- Peiffer JJ, Abbiss CR, Watson G, Nosaka K, Laursen PB (2010b). Effect of a 5-min cold-water immersion recovery on exercise performance in the heat. British Journal of Sports Medicine 44(6), 461-5
- Pérgola PE, Kellogg DL Jr, Johnson JM, Kosiba WA, Solomon DE (1993). Role of sympathetic nerves in the vascular effects of local temperature in human forearm skin. American Journal of Physiology 265(3), 785-92
- Proulx CI, Ducharme MB, Kenny GP (2003). Effect of water temperature on cooling efficiency during hyperthermia in humans. Journal of Applied Physiology 94(4), 1317-23
- Raines J, Snow R, Petersen A, Harvey J, Nichols D, Aisbett B (2010). Pre-shift fluid intake: effect on physiology, work and drinking during emergency firefighting. Article submitted to Medicine and Science in Sports and Exercise.
- Richards D, Richards R, Schofield PJ, Ross V, Sutton JR (1979). Management of heat exhaustion in Sydney's the Sun City-to-Surf run runners. Medical Journal of Australia 2(9), 457-61
- Roberts WO (2007). Exertional heat stroke in the marathon. Sports Medicine 37(4-5), 440-3
- Ross ML, Garvican LA, Jeacocke NA, Laursen PB, Abbiss CR, Martin DT, Burke LM (2010). Novel Pre-Cooling Strategy Enhances Time Trial Cycling In the Heat. Medicine and Science in Sports and Exercise, May 27 [Epub ahead of print].
- Rowell LB (1986). Human circulation: regulation during physical stress. Oxford University Press, New York, NY, USA
- Rubin SA (1987). Core temperature regulation of heart rate during exercise in humans. Journal of Applied Physiology 62(5), 1997-2002
- Ruby BC, Schoeller DA, Sharkey BJ, Burks C, Tysk S (2003). Water turnover and changes in body composition during arduous wildfire suppression. Medicine and Science in Sports and Exercise 35(10), 1760-5
- Sargeant AJ (1987). Effect of muscle temperature on leg extension force and short-term power output in humans. European Journal of Applied Physiology 56(6), 693-8
- Sato KT, Kane NL, Soos G, Gisolfi CV, Kondo N, Sato K. Re-examination of tympanic membrane temperature as a core temperature. Journal of Applied Physiology 80(4), 1233-9
- Sawka MN, Latzka WA, Montain SJ, Cadarette BS, Kolka MA, Kraning KK, Gonzalez RR (2001). Physiologic tolerance to uncompensable heat: intermittent exercise, field vs laboratory. Medicine and Science in Sports and Exercise 33(3), 422-30
- Sawka MN, Young AJ, Latzka WA, Neufer PD, Quigley MD, Pandolf KB (1992). Human tolerance to heat strain during exercise: influence of hydration. Journal of Applied Physiology 73(1), 368-75
- Selkirk GA, McLellan TM (2001). Influence of aerobic fitness and body fatness on tolerance to uncompensable heat stress. Journal of Applied Physiology 91(5), 2055-63
- Selkirk GA, McLellan TM, Wong J (2004). Active versus passive cooling during work in warm environments while wearing firefighting protective clothing. Journal of Occupational and Environmental Hygiene 1(8), 521-31
- Sinclair WH, Rudzki SJ, Leicht AS, Fogarty AL, Winter SK, Patterson MJ (2009). Efficacy of field treatments to reduce body core temperature in hyperthermic subjects. Medicine and Science in Sports and Exercise 41(11), 1984-90
- Smith JA, Yates K, Lee H, Thompson MW, Holcombe BV, Martin DT (1997). Pre-cooling improves cycling performance in hot/humid conditions. Medicine and Science in Sports and Exercise 29(5), S263
- Siegel R, Maté J, Brearley MB, Watson G, Nosaka K, Laursen PB (2010). Ice Slurry Ingestion Increases Core Temperature Capacity and Running Time in the Heat. Medicine and Science in Sports and Exercise, Nov 27 [Epub ahead of print].
- Taylor NA, Caldwell JN, Van den Heuvel AM, Patterson MJ (2008). To cool, but not too cool: that is the question--immersion cooling for hyperthermia. Medicine and Science in Sports and Exercise 40(11), 1962-9
- Tikuisis P, McLellan TM, Selkirk G (2002). Perceptual versus physiological heat strain during exercise-heat stress. Medicine and Science in Sports and Exercise 34(9), 1454-61
- Wimer GS, Lamb DR, Sherman WM, Swanson SC (1997). Temperature of ingested water and thermoregulation during moderate-intensity exercise. Canadian Journal of Applied Physiology 22(5), 479-93
- White AT, Davis SL, Wilson TE (2003). Metabolic, thermoregulatory, and perceptual responses during exercise after lower vs. whole body precooling. Journal of Applied Physiology 94(3), 1039-44
- Wilson TE, Johnson SC, Petajan JH, Davis SL, Gappmaier E, Luetkemeier MJ, White AT (2002). Thermal regulatory responses to submaximal cycling following lower-body cooling in humans. European Journal of Applied Physiology 88(1-2), 67-75

- Wong NH, Chong AZM (2010). Performance evaluation of misting fans in a hot and humid climate. Building and Environment 45(12), 2666-2678

- Wyss CR, Brengelmann GL, Johnson JM, Rowell LB, Niederberger M (1974). Control of skin blood flow, sweating, and heart rate: role of skin vs. core temperature. Journal of Applied Physiology 36(6), 726-33

- Yates K, Ryan R, Martin DT, Dobson G, Smith J, Tumilty D, Hahn A (1996). Pre-cooling rowers can improve laboratory 2000m performance in hot-humid conditions. Sports Medicine Australia Conference Proceedings, pp. 370-371, Canberra

- Yokota M, Berglund L, Cheuvront S, Santee W, Latzka W, Montain S, Kolka M, Moran D (2008). Thermoregulatory model to predict physiological status from ambient environment and heart rate. Computers in Biology and Medicine 38(11-12), 1187-93

7. Appendices

7.1. Survey of Lifestyle Factors

After your have signed the consent form, please provide the following information.

Age: ____________

Gender: Male ☐ Female ☐

How long have you lived in the Northern Territory? ____________

How long have you been a fire-fighter for? ____________

Are you: full time ☐ part-time ☐

How much exercise do you do outside of work? (hours per week) ____________

How well hydrated do you feel?

Well hydrated ☐ Intermediate ☐ Dehydrated ☐

How much fluid have you drunk over the past 24 hours? ____________

7.2. Thermal Sensation

Thermal Sensation Scale Rating

How did the temperature of your body feel during the session?	
1.	Unbearably Cold
2.	Extremely Cold
3.	Very Cold
4.	Cold
5.	Cool
6.	Slightly Cool
7.	Neutral
8.	Slightly Warm
9.	Warm
10.	Hot
11.	Very Hot
12.	Extremely Hot
13.	Unbearably Hot

7.3. Post Exercise Survey

After you have completed final cooling, please answer the following questions:

1. What did you think about your cooling station? (Was it a good method of cooling or not)

2. Were there any changes that you would suggest?

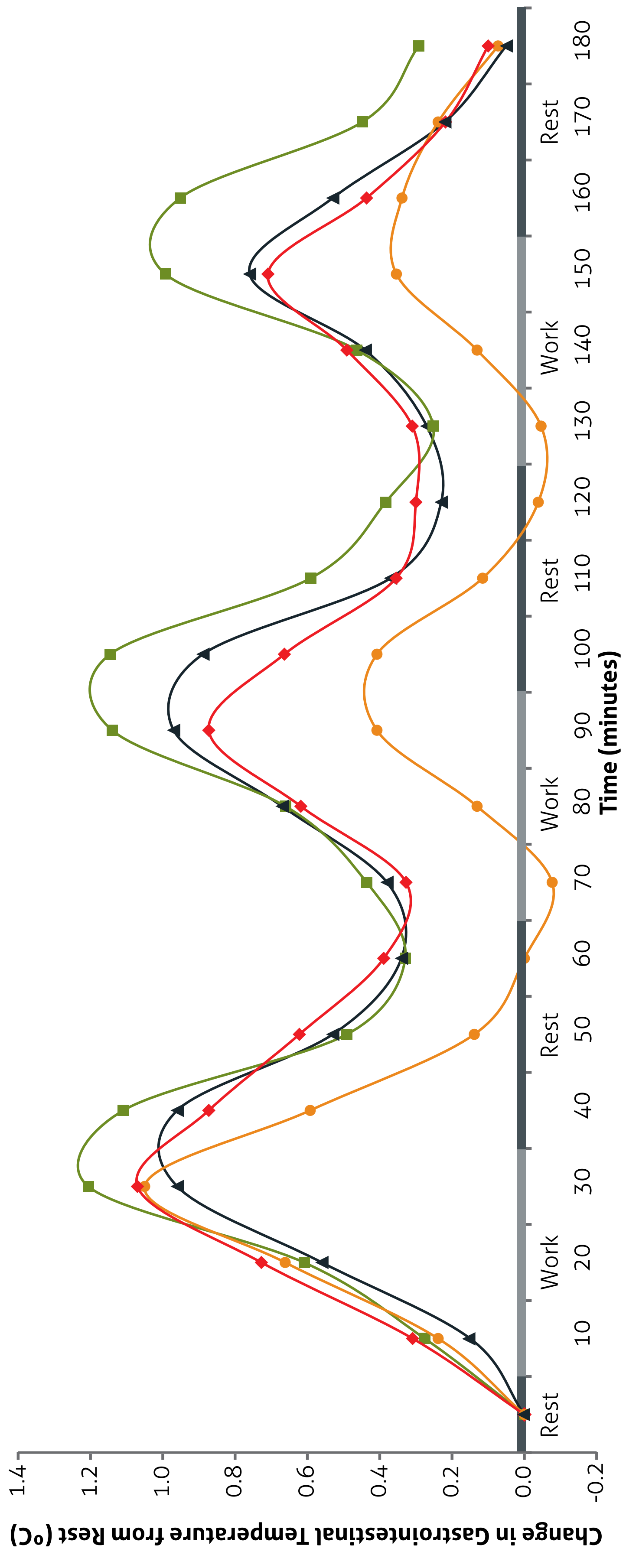
3. Do think that that this cooling method would work in a "real-life" CBR incident?

4. Would you have preferred a different cooling method? If so, which one and why?

Thank you for participating today, please:

- Get your final weight checked
- Provide a post test urine sample

7.4. Figure 16


Shade
Ice Ingestion
Water Immersion
Misting Fan
Change in Gastrointestinal Temperature from Rest (ºC)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
Rest
Work
Rest
Work
Rest
Work
Rest
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
Time (minutes)

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